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OPTIMAL OPERATION OF POWER PLANTS AND ELECTRIC SYSTEMS

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This book covers the problems of optimal control of electric power stations and systems under normal conditions with the use of the management control system (MCS). Ample consideration is given to management at all stages of electric power production, including decision making and short-term planning, on-line control, environmental protection. Major attention is focused on the fundamentals of the modern theory of power system management, primarily its physical and engineering aspects. All the topics envisage a comprehensive use of computers at different levels of management.

The book is to be an aid for students of power specialities who study the course of optimal operation of electric power stations and systems or its separate topics.

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ОПТИМИЗАЦИЯ РЕЖИМОВ ЭЛЕКТРОСТАНЦИЙ И ЭНЕРГОСИСТЕМ

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PREFACE

The textbook, consisting of two parts and representing the authors' combined experience in research and teaching at colleges in Moscow, Novosibirsk, and Kishinev, is intended as an aid for students of power specialities. Part One deals with the peculiarities of power system control based upon management control system (MCS). Part Two is devoted to the problems of optimal operation of electric power plants and systems.

Using a single methodological approach to a wide range of routine management problems with highly computerized electric power systems, the book focuses major attention on the fundamentals of modern theory of power system management. The engineering aspect of the management problem and its mathematical models are comprehensively discussed. The body of mathematics used in the manual corresponds to the syllabi for the specialities being considered.

The optimization problems are solved as applied to all the stages of energy production, decision making, long-term and short-term planning, performance updating, and real-time control. The relationship between the optimal operation of electric power stations and systems as well as that between the environmental protection and the optimal economic activities of an enterprise are considered.

The limited scope of this book has compelled the authors to highlight only the principal aspects of the methodology of developing and operating MCS for energy production, as well as the advanced experience in the computerization of the power systems and pools. For more detailed information on the practical use of MCS, the reader should refer to [1].

Preface and Introduction were written by V. A. Venikov, Chapters 1, 5 and 13 were written by him in collaboration with V. G. Zhuravlev, Chapters 6, 12 with T. A. Filippova. V. G. Zhuravlev wrote Chapters 2-4, 10 and Sections 6.5, 6.9, 7.1, 7.2, 7.9, 9.8-9.10, 12.7. T. A. Filippova wrote Chapters 7-9, 11 and Section 10.4.

The authors

LIST OF ACRONYMS

ACB	area-level control board
ADCS	automatic dispatch control system
ANP	alphanumeric printer
APCS	automatic process control system
BMCS	branch management control system
CAI	computer-aided instructions
CMCS	construction management control system
CU	control unit
DE	directed exhaustion
DP	dynamic programming
DTE	data transmission equipment
ENF	electric network facilities
FMCS	factory management control system
HP	hydro plant
IDPS	integrated data processing system
IIS	integrated information system
IMCS	integrated management control system
IS	information software
MBB	method of branches and boundaries
MC	multiplexor channel
MCS	management control system
MIS	management information system
MMCS	maintenance management control system
NPP	nuclear power plant
OS	operating system
PDS MCS	production, distribution and sale MCS
PLIR	power loss incremental rate
PP	power plant
PP MCS	power plant management control system
PS MCS	power system management control system
PSP	pumped-storage plant
PTA MCS	production and technical activity management control system
PU	peripheral units
RTIC	real-time information complex
SAS	specialized application software
SC	selector channel
SMCS	sale management control system
SSI	state system of instruments
TC	telecontrol
TEI	technico-economic index
TI	telcinterlocking
TM	telemetry
TMD	telemetry device
TPP	thermal power plant
TS	temporary storage
TSCC	time-sharing computer center
UP	utility program
USC	unified system of computers
USSR NMCS	national management control system of the USSR
USSR PG CCD	central control department of the USSR power grid

INTRODUCTION

Performance control. The present book is entitled "Optimal Operation of Power Plants and Electric Systems". The word "optimal" is far from being a mere synonym to best. It implies that a certain object (process) meets particular requirements, which are the optimality criteria, better than other objects (processes). Thus the notion of optimality is relative and involves a comparison of objects or processes with respect to some aspects (characteristics).

The comparison of the processes is confined to such problems the solution of which should manifest, quantitatively as a rule, to what a degree or by how many times one process is more favourable than the other or others regarded in the light of optimization. The ultimate goal of solving such problems is to maximize the economical feasibility for the country as a whole or to ensure in particular applications the minimum or maximum values of some parameters of the process, e.g. decrease the fuel consumption to the lowest possible degree in the energy generation process without cutting power supplies. On some occasions the quantitative terms of the optimization prove insufficient so that certain general qualitative characteristics have to be resorted to. An example is the optimization of the ecological effect of the energy generating unit, when the system is designed or operated with a view to minimizing the pollution.

The power system processes are usually described by a set of ordinary differential and algebraic equations. The same equations may be successfully used for describing with a reasonable realism some economical processes in the so-called macroeconomical models which represent the economy of the country. When considering the processes within the economic system, account must be taken of the disturbances, both external (changes in the composition of raw materials, increase or decrease of resources) and internal (inadequate accomplishment of tasks at preceding stages of management, failure of the equipment). The disturbances necessitate the on-line control of the system, e.g. of the energy generation system. The object of such a control is to fulfill the production program in view of the particular situation with the aid of the operations research. The *operations research models* are employed to solve these problems. The operations research dynamic model comprises two parts intended to find the coordinated optimal solutions: the first part (the on-line control)—for the present moment of time (hour, shift), the

second part (planning models)—for the whole forthcoming period (day, week, quarter, year).

The period of the operations research is selected depending on the reliability of the load prediction and the state of production and is divided into stages. The operations research problems are solved on a moving-time basis. The planning models are used for finding the optimal control technique for the entire period, which is implemented at the first stage. After this stage is completed, a decision is made again for the entire period with a one-stage time shift.

The effectiveness of the operations research depends on the possibility of predicting the system operating conditions at the on-line control stage. Therefore, the number of the time stages at the solution of the operations research problems should be selected on the basis of a reasonable compromise between the accuracy requirements and the computation costs since the principal disturbances may be predicted with a minimum risk only for a limited period of time.

The operations research problem is complicated by the specific features of the production and is a multi-dimensional non-linear programming problem which is extremely difficult to solve.

The problems of planning the performance of electric power stations and systems make a part of a great class of the optimal control problems aimed at maximizing the technical and economical effectiveness of management control systems (MCS) and process control (functioning problems). Among the problems relating to the electric power grids are those requiring the application of the optimization methodology:

(1) determining the optimal expansion strategy—construction or modernizing of the systems and separate objects included in them. Among these are selecting the location and power of new plants, substations and transmission lines, planning the terms of putting them into operation;

(2) selecting the best configuration of the power network integrating separate subsystems or transmitting and distributing power within the system;

(3) distributing loads among separate electric power stations of the existing or planned system;

(4) determining the strategy of the best use of the resource (types of fuel, etc.);

(5) selecting the best routes of transfer of various cargoes, including fuel;

(6) determining the opening points for the two-way supply lines;

(7) selecting the routes of inspection of the electric power installations, etc.

The energy production optimization problems may relate either to transient conditions when sets of differential equations are to be necessarily used, or to the steady-state conditions, when it is pos-

sible to confine to the sets of algebraic equations. Optimization may be applied to the operation of the existing power systems including plants, substations, transmission lines, networks and consumers, and to the stage of designing, planning and prediction of the systems being constructed.

Optimization methods. Among the Soviet scientists who have greatly contributed to the optimization theory and practice are G. M. Krzhyzhanovsky, V. G. Aivazyan, V. V. Bolotov, V. M. Gornstein, V. I. Gorushkin, T. L. Zolotarev, I. M. Markovich, N. A. Melnikov, M. P. Feldman, V. G. Holmsky, O. V. Shcherbachev, et al.

When optimization problems became urgent for the power industry in the 1920s, they were solved on the basis of the mathematical methods of determining the extrema of functions and functionals by the analytical study of the connections between separate parameters (variables) characterizing the process. When solving such problems the engineers referred primarily to the methods of calculus of variations and first of all to Lagrange's method of multipliers for finding the conditional (relative) extremum of a continuous function of many variables when the variables are subject to the subsidiary conditions in the form of equations (coupling equations).

Lagrange's method of multipliers allows finding such a system of equations which is satisfied by the extremum of the function $f(X_1, \ldots, X_k)$ at a set N determined by the system of equations $g_i(X)$ for $i = 1, 2, \ldots, m$.

To find the extremum point defined at a set N by certain vector $\mathbf{X}$, it is necessary to find m numbers $\lambda_1, \ldots, \lambda_m$ which would satisfy with the vector $\mathbf{X}$ the following system of $(m + n)$ equations in $(m + n)$ unknowns:

$$\frac{\partial f(\mathbf{X})}{\partial \mathbf{X}_j} + \sum_{i=1}^{m} \lambda_i \frac{\partial g_i(\mathbf{X})}{\partial \mathbf{X}_j} = 0$$

$$j = 1, \ldots, n, \; g_i(\mathbf{X}) = 0, \; i = 1, \ldots, m$$

These equations were developed as the extremum conditions for the Lagranian function $L(\mathbf{X}, \lambda) = f(\mathbf{X}) + \sum_{i=1}^{m} \lambda_i g_i(\mathbf{X})$, where numbers $\lambda_1, \ldots, \lambda_m$ are called the Lagrange multipliers.

The task of the engineers was to adapt the Lagrange method to optimizing operation of the power generating units, in particular to finding the optimal distribution of load between several units. For instance, if a boiler house comprising n boilers must generate heat in the amount of Q, MJ/h, and the fuel consumption B_i of each (ith) boiler is known, the minimum of the total fuel consumption $(\min \sum_{i=1}^{n} B_i)$ is found by the Lagrange method which provides for determining the extreme value of the objective function. To this

end, by equating to zero the partial derivatives of the Lagrange function being changed to suit the problem being solved, it is possible to find that the condition for the relative minimum of the total consumption of fuel will be the identity of relative increments of fuel consumption on all the units, i.e. the value $b_i = \frac{\partial B_i}{\partial Q_i} = \text{idem}$, where B_i is the unit load. This was the first simplest solution of the optimization problem in the power industry which is considered at greater length in Part Two of the book.

Special methods constituting a division of applied mathematics were used for solving more complex problems of optimization which evolved with the development of power industry. These methods are based on the calculus of variations. They allow finding the extrema of composite functions by employing special techniques for studying the analytical relationships between the variables. However, these methods cannot determine the absolute extremum and cannot be used for the multi-extremum problems. A sufficient condition for testing for a local extremum (maximum or minimum) is that the first derivative $f'(x_0)$ be zero at the point x_0, while the second derivative $f''(x_0) \neq 0$. If $f''(x_0) > 0$, the local extremum is the minimum, if $f''(x_0) < 0$ the maximum. If at the boundary of certain region N the value of the function is less than the absolute minimum, it is called the minimum value of the function in the region. The methods of finding an absolute extremum for the functions having a number of local extrema have not yet been extensively developed so that the practical optimization problems are solved with various simplifications which specify the peculiarities of the system to be optimized.

The methods of calculus of variations cannot be used for solving the single-extremum problems if the subsidiary conditions (constraints) are in the form of inequalities. At the same time, all branches of technology, including power engineering, demanded introduction of the ever rising number of the constraints inequalities. This promoted special methods for reviewing and comparing a multitude of possible ways of planning and forecasting the optimal development of the power industry or optimal control of the system.

The power industry optimization problems were becoming more and more confined to the operation problems—accomplishment of certain operations, i.e. effecting a system of operations united by a single concept and aimed at a particlar objective. The degree of achievement of the objective is described by a certain function (*objective function* or *criterion*) assuming real numerical values. If this function is defined mathematically, the aim of the operation is to obtain the extremum of the said function, i.e. the objective function. To act upon the said function in the desired direction, there are definite active means—controlled variables $x_{con.1}, \ldots,$

$x_{con,\,n}$ by which the output variables $y_1, y_2, \ldots, y_m$ being the variables of the objective function may be affected. The operation results are also affected by uncontrolled variables $x_{1,un}$, $x_{2,\,un}$, $x_{k,un}$ which determine the conditions under which the operation is carried out. The extreme values are found with the use of the *mathematical model* of the process or a group of processes (event) being studied (optimized).

The mathematical model is a representation of the process being considered in the form of some functional relationships

$$y_i = \varphi_i(x_{con,1}, x_{con,2}, \ldots, x_{con,n}, x_{1,un}, x_{2,un}, x_{k,un})$$
$$i = 1, 2, \ldots, m$$

It is necessary to know the relationships which represent the constraints in the form of equations and inequalities. The values of the controlled variables for which such constraints are satisfied are called the permissible decisions. The goal of the optimization is to find a technique which would allow us to select from a plurality of permissible decisions such decisions whereat the values of the controlled variables would satisfy the assigned constraints and the objective function would become the maximum or minimum. An intricate structure of the mathematical model with a great number of controlled and input variables (some of them being nonlinear and discrete) and the fact that the controlled or output variables are represented by functions (scalar, vector or matrix) rather than by numbers considerably complicate the decision making technique. The general methods of finding the function extremum in the presence of constraints are elaborated by the mathematics branch commonly referred to as the theory of mathematical programming and including linear programming, nonlinear programming, dynamic programming, stochastic programming.

One should bear in mind that the optimization methods are based on the so-called *systems approach* which resides in the combined consideration of all the parts and functions of the system in harmony. In this case the partial interests should be inferior to the general ones. As applied to the electric power systems, it implies that the optimal decisions should be made to satisfy the needs of the power supply systems, power transmission and distribution systems and the systems of power consumers who are to receive the energy of a definite quality with a guaranteed reliability of supply.

The optimization methods have found wide application in industry after the appearance of the high-speed computers. These machines offered grounds for elaborating and developing methods of finding the extremum of the function or functional under study in different ways. At first, simple numerical optimization methods were used for finding the extremum by the exhaustive search of vari-

ous combinations of values of the independent variables and calculation of the corresponding values of the objective function. The analytical relationship between the functions and the argument may be unknown. However, the exhaustive search of possible variants is very complicated and requires considerable time even with high-speed computers. Therefore, the methods of mathematical programming mentioned above have become of a particular interest for solving the practical tasks. The properties of these methods allow one to perform an organized search of the variants. Among such methods is a method of linear programming proposed by the Soviet scientist, the Lenin prize and the Nobel prize (1975) winner L. V. Kantorovich and the US scientist G. D. Dantzig. The method provides for finding the optimum solution at a linear form of the objective function and in the presence of linear constraints (for single-extremum problems).

The linear programming problem can be mathematically represented as follows. Let the mathematical model be written in the form of a linear relationship

$$E(x) = a_1x_1 + a_2x_2 + a_3x_3 + \ldots + a_nx_n = E(a, x)$$

We must find the values of $x_1, \ldots, x_n$ at which the extreme value of function $E(x)$ may be ensured under constraints

$$b_{i,1}x_1 + \ldots + b_{i,n}x_n \leqslant d_i$$
$$b_{k,1}x_1 + \ldots + b_{k,n}x_n = d_k$$
$$b_{l,1}x_1 + \ldots + b_{l,i}x_n \geqslant d_l$$

The constraints present in the linear programming problems are sometimes complemented with conditions of *non-negativity of all or some of the variables* $x_j \geqslant 0$, $j = 1, \ldots, p$.

The objective function $E(a, x)$ is sometimes referred to as the criterion or functional of the linear programming problem.

One of the most common linear programming problems is the so-called *transportation problem*. This problem is solved to find the most economical way of transporting some products from warehouses to the consumers. In this case it is assumed that the transportation cost per unit product to the assigned destinations is known.

The development of the theory and practice of the power industry optimization problems has become more and more urgent as the power systems were integrated into pools and later into grids.

When analyzing the performance of the electric power pools and grids it was necessary to find the extremum of the nonlinear function on a set of points which satisfy the nonlinear inequalities. This has given birth to the theory of extremum in nonlinear constraint problems. For the first time the conditions for finding such an

extremum were determined by Kuhn and Tucker. They are postulated as the *Kuhn-Tucker theorem of necessary conditions.*

If E (X) is an objective function, g (X) are the constraint inequalities, g (X) being a convex function, then to make point $\mathbf{X}_0$ optimum, i.e. to ensure that $E(\mathbf{X}_0) = \min E(\mathbf{X})$, it is necessary and sufficient that there exist a point λ_0 or a pair of points $\{\mathbf{X}_0, \lambda\}$ such that form the saddle of the Lagrange function

$$L(\mathbf{X}, \lambda) = E(\mathbf{X}) + \sum_{i=1}^{k} \lambda_i g_i(\mathbf{X}_i)$$

where k is the number of constraints.

This means that $L(\mathbf{X}_0, \lambda) \leqslant L(\mathbf{X}_0, \lambda_0) \leqslant L(\mathbf{X}, \lambda_0)$ for any $\mathbf{X}$ and all $\lambda_i \geqslant 0$. It is often easier to find the saddle point than to minimize the objective function at given constraints. If functions E (X) and L (X) are differentiable, the saddle point is found from the condition

$$\begin{cases} \dfrac{\partial L}{\partial \mathbf{X}_j} \mathbf{X}_j = 0; \\ \dfrac{\partial L}{\partial \lambda_i} \lambda_i = 0; \end{cases} \quad \begin{cases} \dfrac{\partial L}{\partial \mathbf{X}_j} \geqslant 0; \\ \dfrac{\partial L}{\partial \lambda_i} \leqslant 0; \end{cases} \quad \forall_{i,j}$$

If the constraints are only in the form of equations, the Kuhn-Tucker conditions are confined to the use of a regular rule of the Lagrange multipliers.

The Kuhn-Tucker theorems were used in the power system optimization problems with some simplifying assumptions. For instance the function of the power production cost at thermal stations was assumed convex, the outage losses were neglected, while the constraints of the generator maximum and minimum output and the constraints of the voltage levels at the network nodes were taken into account. The methods of solving the minimizing problems in which the minimized function is convex and defined on a convex set are usually called convex programming.

Complicated solutions of multi-extremum problems which are of great practical interest caused numerous attempts to find new methods of solving that would be applicable to engineering practice. R. Bellman (USA) developed a method of solving such problems, which he called *dynamic programming.* According to this method the optimization process is considered as a multistage process: the decision is made successively stage after stage. This decreases the volume of the required calculations and allows one to determine the absolute minimum in the multi-extremum problems. The dynamic programming involves the techniques of sequential analysis of variants. The analysis is carried out with the use of procedures aimed at rejecting all possible decisions that do not include the optimal one on the

basis of indirect estimation. As these procedures are executed, a plurality of equal-merit decisions are gradually contracted to one or several variants which are directly compared to each other. The principle of gradual rejection of variants with a view to choosing the preferable one is more natural for engineers and it has found a wide application. An appropriate mathematical theory converts this general approach to a system of formal procedures which allow one to build efficient algorithms.

The multistage methods include the so-called network programming methods which provide for optimizing the design and construction of complex installations by several contractors.

There are also methods of solving the optimization problems which are based on game theory. Such methods prove most successful in conflict situations when the interests of two (or more) parties are contrary or incompatible. Game theory originated concurrently with probability theory as far back as the XVII century, became an independent branch of mathematics in the XX century after the works of Von Neumann and Morgenstern of the USA, and has been recently employed in power production problems.

The development and implementation of the optimization methods in the power industry is a vital technological and economic task. Heavy capital outlays involved in the power industry make particularly urgent the problems of rational utilization of the investments and improvement of their effectiveness. Designing and operation of the power systems and pools represent the most complex technological and economic problems which are always dynamic, nonlinear and multiform.

Efficiency of management. The best local criterion of the economic optimality when solving such problems is the economic *effectiveness*, i.e. the social usefulness of the creation and employment of the power system or structure. The changes of the effectiveness during a certain finite period of time (e.g. year) is the most convenient characteristic of the economic activities. However, the problem of the optimization is very complex and to solve it a difference between the economic effectiveness and the social effectiveness should be understood. The economic effectiveness is only an element of the social effectiveness and is far from being equivalent to the latter.

In analyzing great systems such as power production, the socioeconomic effectiveness of the measures being taken is sometimes also considered. Meant by the socioeconomic effectiveness is a complex characteristic of the final economic results obtained in the productive and non-productive branches of the national economy. This involves measures aimed, apart from improving the economic indices, at solving certain social problems.

The calculations of the socioeconomic effectiveness require a systems analysis of all principal results of the decisions taken with

tracing interconnections between the objects under study and other subunits of the planning and management hierarchy of the national economy. The result of the combined measures may radically differ from the sum of the results belonging to separate components because of the complexity of the socioeconomic processes. As the complexity rises, the influence of such a total result generally strengthens.

The complex characteristic of the socioeconomic effectiveness of the measures taken in the productive and non-productive branches of the national economy is the appropriately formulated system of cost and real indices being representative of the intensity of utilization of the principal resources (material, labour, financial) and the results obtained (social, economic, ecological, etc.). Thus the socioeconomic effectiveness of measures and solutions of the planning, design or operation problems should be determined on the basis of comparison of all the results obtained and expenses involved in the entire system of the national economy and in its subsystems (e.g. in the power industry).

The systems analysis of the socioeconomic effectiveness necessitates the interrelated calculations of its relative and absolute indices. The relative indices serve for comparing various possible alternatives, while the absolute indices are used to analyze the correctness of the premises and the reliability of the results obtained. When calculating the socioeconomic effectiveness due consideration should be given to the comprehensive effects of the time factor, the long-term nature of the socioeconomic processes, dynamic changes of costs and results involved in different measures.

The estimation of the socioeconomic effectiveness should be based on that only the objective trends in the development of the respective processes are the determinants. In other words, the effect of indeterminacy on the technological-and-economic indices of various alternative decisions should be taken into account. The methods of determining the socioeconomic effectiveness often take the form of partially formalized man-machine (ergodic) evaluation procedures with an extensive use of the economic-and-mathematical models.

The effectiveness is evaluated with the aid of the criterion of effectiveness which is an additional restriction showing an efficient way to achieve the objective: for instance to change the system from state A to state B within the shortest time or at minimum expenses possible, etc. The criterion of effectiveness is a formal representation of the aim being sought. The criterion of effectiveness is sometimes referred to as the criterion of management quality, optimization or objective function. Meant by the objective in this case are certain programmed results. For instance, when changing the system from state A to programmed state B it is desirable to achieve the objective with a maximum effectiveness and neutralize the external dis-

turbances. To this end, a certain measure of quality of the objective achievement is introduced, this being the criterion of effectiveness. To achieve the objective it is necessary to meet a number of requirements called *restrictions* or *constraints*, e.g. technological parameter constraints. If a power system including n electric power stations supplies power and heat to the consumers, the management objective is to ensure troublefree meeting of the consumer's demand for power and heat. The criterion in this case is the maximum profitableness of the power system operation. The constraints to be satisfied are confined to that the obtained optimal load of each station is inside the permissible limits.

The *criterion of effectiveness* should be simple, measurable (normalizable), be capable of numerically characterizing the degree of accomplishment of the system functions and provide for evaluating the influence of various factors upon the effectiveness of the system. It should feature a narrow dispersion to allow a comparison of the similar-purpose systems. A complex economic object is described by a number of different criteria. They are not confined to each other so that a system of criteria is needed for describing and comparing the systems.

Mathematical model. The model of the production process may be represented in the form of a set of relationships (equations) which interrelate the production process parameters, the input and output variables and the constraints. A complete mathematical model of the production process comprises the following relationships.

1. Coupling equations describe the production process of the system and represent the output variables versus input variables.

2. Constraints show the permissible ranges of the input and output variables of the system, the production process conditions; these may be linear or nonlinear, be written in the determinate or stochastic form.

3. Effectiveness equations (objective function) represent the correspondence between a decision and the management objective.

4. Adaptation equations. If the management system is adaptive, which is generally encountered, the adaptation resides in considering the merits of the previously found successful variants of the system behaviour and trying to reproduce them under similar conditions or at least to minimize the discrepancies between such variants. Not only the variables but also the structure of the management system are subject to change in adaptation. The adaptive management requires additional memory for storing and analyzing the results of past activities.

5. Management equations determine the optimal law (algorithm) of management and show in general the optimal output variables versus the controlled and uncontrolled variables. The search of the management law is the final stage of the system optimiza-

tion. The optimization methods (model optimization element) are used for the search.

Simulation model. In addition to complete models simplified mathematic models are frequently used. These contain only some of the five groups of equations described above. In particular the simulation or evaluation models are widely used. They do not include the optimization element and serve only to enable the operator to estimate different variants of the system behaviour on the basis of the set of external factors or control variables. The simulation model contains the coupling and constraint equations and involves the calculation (not optimization) of the objective function. The search of the optimal variant of management with the aid of such models is greatly dependent on the skill of the operator.

The type of model depends on the information available, its reliability, the method of obtaining and the method of minimizing being used. Let us consider three cases.

1. When a situation is simulated, the most preferable behaviour of the system is found; this is the case of effectiveness of the optimization model; the final decision is given wholly by the machine.

2. A situation model is constructed in the form of a simulation model when it is impossible to obtain a single answer as to the best method of management; in this case the decision is made by the man.

3. The situation cannot be simulated on the whole due to the lack of information or insufficient understanding of the processes under study; in this case it is good policy to divide the problem into subproblems and try to construct simulation models for them.

The power industry development models should reflect the relationships linked with the influence of the social processes as well as the possible effect of the power industry development on the social phenomena. As it was mentioned above the basis for any process, including the social one, is the objective. The purposeful action is impossible without control. However, any control is based on *processing of information*, which therefore represents a definite logic component of the process. Practically each process involves two components—physical and informative (logic). The former characterizes the conversion and transfer of material masses, while the latter, processing of information. The physical component is strengthened by developing new improved machinery, using novel energy sources and increasing the power availability per man. The logic component may be strengthened by providing means for more effective processing of information. Thus, the effectiveness of any process depends both on the physical and logic components, so that to increase the effectiveness of a process both the physical and logic components should be improved.

The growth of systems operated by the man brings about difficul-

ties in information processing since the man's capabilities in this respect are limited. Therefore it became necessary to increase the efficiency of information processing, i.e. to strengthen the intellectual capabilities of the man and mankind. The process of increasing the effectiveness of management became particularly intensive in the second half of this century, when the complexity of the management problems has drastically increased. The complexity of the economical management problems is known to grow more rapidly than the number of people engaged in the economy. Thus, the complication of management increases its labour input. There comes a situation when the existing demands of management come in conflict with the available resources of the living labour. For instance, the Soviet scientist V. M. Glushkov gives the following estimates: the lower boundary of complexity of the management problems in this country at the beginning of the 1970s was about 10^{16} arithmetical operations per annum. The upper boundary of the average capacity of the human brain in information processing is about 10^{8} operations per annum. To accomplish 10^{16} operations per annum at least 10 billion of people are needed. This conflict may be settled either by decreasing the quality of management or by improving the management techniques.

The technological processes must be improved and optimized for saving living labour input in management. The promising way of increasing the responsiveness of management is computerization. It should be borne in mind that the computers will yield good results only in case of sophisticated programming. The electronic computers are the only means for accumulating, storing and high-speed processing of information. They can process any information in the interests of management with equal success without determining the conditions of processing (the relationship between the hardware and the software is similar to that between the television equipment and program contents). The computers are not self-serving units. They cannot develop programs or function jointly with the communication channels and other technical devices. All these functions may be performed by the computer only through the use of a combination of algorithms represented by the information processing programs, i.e. software.

Thus, the management special software system, more commonly referred to as the management information system (MIS), is a representation of the objective laws of development of the society and science which provides for directly and timely implementing them in practical management. This system is a materialized collective intellect and is intended for converting the achievements of the science and technology into a form suitable for evaluating the correctness of particular decisions of management.

The management information system is intimately associated

with the control processes to which we also refer the optimization process. This system is a connecting link between the control body and the controlled objects; it executes the function of formalized processing of information for raising the quality of management and improving the results of functioning of the controlled objects.

The construction of the mathematical model completes the process of formalizing the objective laws of management. The information model comprises a structural representation of the said laws, while the mathematical model brings them to the information processing algorithms. At the stage of constructing the mathematical model, the management information system becomes adaptive by including special-function algorithms into the mathematical model. The adaptation to the data stored in the data base is confined to the algorithmic analysis of the correctness and exhaustiveness of the initial data, and elimination of results of probable uncertainty of the source data. The adaptation to the real time is achieved by using several different modules which perform the same functions with different precision.

A combination of the information and mathematical models gives a complete description of the formalized rules of data processing in the interests of management. The quality of the mathematical model is determined by its ability to produce optimum recommendations for making the management decisions.

The management information system is the basic means for increasing the intellectual potential of a man engaged in management.

Part One

EMPLOYMENT OF MANAGEMENT CONTROL SYSTEM IN POWER AND HEAT GENERATION

1

POWER AND HEAT SYSTEMS AND THEIR OPERATION

1.1. Basic Definitions

Consider some definitions.

Power and heat system is a combination of electric power stations, substations and consumers of electric power and heat interconnected by electric and heat networks.

Power system is a combination of electric power stations, substations and consumers of electric power, interconnected by electric networks.

Power and heat system structure. Distinction is usually made between installed (rated), available and operating powers of electric power stations. The available power is equal to the installed power less power interruptions and restrictions. The operating power is the available power minus the power of the station equipment being repaired. The power interruption (e.g. because of the boiler heating surface scaling) differs from the power restriction (e.g. due to overheating of water at the power and heat generating stations) in that the station personnel can affect the interruption while the restrictions are beyond their control.

The power and heat system installed power P_{ins} is equal to the sum of the installed rated powers of the system power stations P of all types:

$$P_{ins} = P_{hyd} + P_{con} + P_{p/h} + P_{nuc} + P_{g/t} + P_{p/s} + P_{other} \tag{1.1}$$

where *ins* stands for installed, *hyd* hydroelectric, *con* condensation, *p/h* power and heat, *nuc* nuclear, *g/t* gas-turbine, *p/s* hydroelectric pumped storage power stations. Tidal, geothermal, wind, and diesel plants come under other classification.

Divide both sides of Eq. (1.1) by P_{ins} and denote $P_i/P_{ins} = P_{i*}$, then the equation

$$P_{hyd*} + P_{con*} + P_{p/h*} + P_{nuc*} + P_{g/t*} + P_{p/s*} + P_{other*} = 1 \tag{1.2}$$

will determine the structure of the system. The installed power of the electric stations in the USSR was 217.5 mln kW in 1975, while the structure of powers on the whole was characterized by the following average figures:

$$P_{con*} = 0.473,\ P_{p/h*} = 0.276,\ P_{nuc*} = 0.022,$$
$$P_{hyd*} = 0.186,\ P_{other*} = 0.043$$

By the end of 1980 the installed power of all the electric power plants P_{ins} was 266.7 mln kW, and the power facility structure was as follows:

$$P_{con*} = 0.465,\ P_{p/h*} = 0.240,\ P_{nuc*} = 0.075,$$
$$P_{hyd*} = 0.190,\ P_{other*} = 0.03$$

A comparison shows a considerable increase of the nuclear station fraction in the structure. Depending on the local conditions (fuel cost, heat consumption, water resources, etc.), there may be different optimal power structures which would require minimum expenses for the construction and operation of the power and heat system. The search of the optimal structure is a vital and difficult problem of the power system designing. This book does not deal with this problem.

Service properties of electic power stations. Let us consider the principal requirements imposed by the power system on the electric power stations.

—prolonged operation at rated and minimum power under any operation conditions;
—overloads under certain conditions;
—easy stoppage and starting of power generating sets;
—rapid reaching of the rated load and load variations at minor losses of efficiency in regulation;
—high reliability of operation.

Let us consider how these requirements are met by different types of electric power stations.

The service properties of *condensation power stations* are dictated by their components: a steam generator, a turbine and an electric power generator. The rated power of the steam generator depends on the quantity and properties (moisture and ash content) of fuel, restrictions of the heating surface condition (slagging, permissible heating, priming), reduction of the steam generator efficiency at maximum load, condition of the auxiliary equipment (feed pumps, smoke exhausters, coal mills), etc.

The lower limit of the load decrease in the modern steam generators is defined by the firing stability (flame-out hazard) and stability

of the hydraulic and thermal conditions of the heating surfaces (departing from the calculated zone of steam generation in straight-through boilers, obstructed circulation in drum boilers).

To decrease the load lower limit to 0.5-0.65 P_{rtd} (pulverized coal) and to 0.35-0.4P_{rtd} (gaseous and liquid fuel), the steam generators are made with sectional cyclone furnaces, forced regulation of steam superheating, special steam-jet atomizers, etc.

The maximum power of a steam turbine is determined by the temperature and pressure of live steam, vacuum in the condenser (depends on the cooling water temperature), the condition of the condenser and blade system surfaces which affect the turbine efficiency. In summer, a high temperature of cooling water may limit the maximum power of the turbine. The minimum power of the turbine is established to preclude overheating of the low-pressure stage blades.

The maximum power of the electric generator is limited by the maximum current of the rotor or stator. It is also affected by the ambient temperature. On the whole the maximum power restrictions of the turbine-generator set are more likely to be imposed by the turbine in summer (increased temperature of cooling water) and by the boiler in winter (increased moisture content of fuel).

The time of starting the set from the outage is determined primarily by the steam turbine: the decreased clearances between the rotating and stationary parts and temperature stresses in the turbine housing. To decrease the time spent for starting, the temperature difference over the wall thickness and flange width of the turbine housing should be maintained within the permissible range. The start-up period is also shortened by starting the turbine with varying steam conditions.

Approximate Characteristics

Characteristic	Power	
	Base-load condensation	Nuclear
Unit power of turbo-generator set/maximum power of station, MW	1200/6400	1000/4000
Specific outlay, rouble/kW	130-150	250-290
Equivalent fuel rate, g/(kW h)	300-320	—
Efficiency, %	30-35	30-33
Power production cost, kop/10 kW h	4-6	5-8
Maximum permissible reduction of load, %	20-50	20-30
Hot start time, min	200-330	—

The performance of the *power and heat stations* is determined by the interrelation between the electric and heat powers which is a function of the type of the turbines, live steam conditions and steam pressure in the regulated heat extraction taps.

The *nuclear power plants* become an important component of power systems. The slewability of such stations is low because of the impossibility to decrease the load rapidly and the presence of the transient period in the reactor operation. The direct and induced radioactivity of the equipment complicates servicing of the nuclear plants. A positive feature is a low dependence of the station on the environment and fuel supply conditions.

Hydroelectric stations take a place apart in the operation control system owing to their high slewability, high efficiency and low regulation losses, possibility of complete automation and group control, and very high start-up speed. The significance of such stations is diminished by the dependence of the energy resource available (river run-off) on the chance factors and the dependence of the power parameters on the operating conditions of the water consumers.

Some specifications of electric power stations of different types are given in Table 1.1.

Concentrated and hydrothermal power systems. For convenience we shall consider hereinafter a simplified type of the power and heat system. Let us regard a system in which the power stations and load nodes are integrated by such a network whose capacity restrictions and losses may be neglected at the optimization of load distribution. Such a power system is called a concentrated system.

The power and heat system comprising thermal (usually condensation-type) and hydroelectric stations is often referred to as a hydrothermal or mixed power and heat system. Contrary to it a purely

Table 1.1

of Electric Power Stations

station type				
Power and heat	Hydroelectric	Pumped storage	Geothermal	Tidal
250/1500	640/6000	125/1200	300/1200	250
300	300-350	200	80-110	120
130-220	—	1.3×320	450-550	300
40	90-92	60	20-27	32-42
—	0.3-1.3	—	—	—
10-15	70	70	100	80
—	1-2	2-3	15-40	30-180

thermal system which does not comprise hydroelectric stations constitutes a next stage of simplification. We shall be considering all these systems.

Power and heat system operation. At any instant of time the power and heat system is in a certain state which is defined by a set of state variables. The variables assume definite numeric values chosen from a certain permissible population. We shall distinguish the state variables and the condition variables.

The *state variables* represent the parameters of the structural components of the power and heat system (rated capacities of generators, transformers, synchronous condensers, cross-sectional area and length of transmission lines, rated voltages of equipment, etc.). The state variables are uncontrollable when meaning operation of the power and heat system, but they become controllable if applied to the expansion of such systems.

The *condition variables* are the instantaneous values of the power and heat system characteristics measured at a given instant of time. The condition variables are divided into process variables and electrical variables. The examples of process variables are levels of water (heads) at the hydroelectric stations, openings of the guide vane assemblies of hydraulic turbines, flow rate of steam and cooling water at the thermal power station, etc. The examples of the electrical variables are voltages at separate points of the network, resistive and reactive loads of nodes, line currents, transformation ratios, etc.

The system change-over from one state to another is called process. It occurs under the action of the control signals or external disturbances. There are normal and emergency processes. This book deals only with the normal processes.

The *power and heat system operation* is a combination of states and processes of change-over from one state to another. A fixed state of the power and heat system is similar to a frozen picture of its continuous operation process. It is assumed that the behaviour of the system may be characterized with a sufficient completeness by a set of such pictures which are representatives of the system states. Usually the most characteristic states are chosen: the normal working day operation, maximum, minimum, post-emergency operation, etc.

Substitution of the continuous operation with a set of characteristic conditions is inevitable and is used when designing and managing the system. Such a substitution is not always a rough approximation: the problem is how many characteristic conditions are needed, how to choose them and how to measure the required condition variables to describe a complex process of the power and heat system behaviour so that the error does not exceed an assigned limit.

1.2. Load Curves

The load of the power and heat system is variable. There are daily, weekly and annual variations of the load. The daily load variation may be represented by a daily load curve illustrating the changes in the resistive and reactive loads of the power and heat system during 24 hours. Four specific types of the load curve are usually distinguished: normal working day curve, Saturday curve, Sunday curve and Monday curve.

The *daily load curve* (Fig. 1.1) usually has two load peaks—morning and evening, and two valleys—day and night. The lower part of the curve is called base line, the upper, peak (sometimes the half-maximum zone is also distinguished). The load curve is characterized by a number of values. We shall be interested in the value γ which is equal to the ratio of the mean power P_{mean} to the maximum power $P_{\max}$:

$$\gamma = P_{mean}/P_{\max} \qquad (1.3)$$

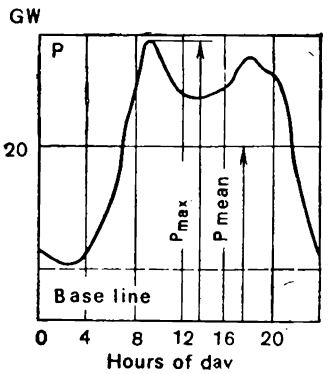

Fig. 1.1. Example of daily load curve

It characterizes the density of the load curve.

The *weekly load variation* is explained by that the system load drops from Friday to Sunday and then rises drastically on Monday. As regards the month, the load usually rises after the end of the second ten-day period to drop somewhat by the first ten-day period of the next month.

The *annual variation* is easily determined if considering the year run of the daily load peaks of the system. To this end, plot several characteristic curves for a normal working day and interconnect their peaks (Fig. 1.2). Transfer the curve to a separate sheet. Now the load drop zone is vividly manifested. The system with a great fraction of agricultural loads may have no summer drops. A similar situation occurs if the system is loaded with a plurality of air conditioning units. The load drops offer favourable conditions for servicing the equipment of the power and heat systems. The load drop zone is often called the equipment maintenance zone (or maintenance valley).

An important characteristic of the system operation conditions is the annual number of hours $T_{\max}$ of utilizing the maximum power. It is found by dividing the annual power production E_{year} by the

annual peak load $P_{\max}$

$$T_{\max} = E_{year}/P_{\max} \tag{1.4}$$

According to the value of $T_{\max}$, the systems may be divided into three groups: (1) with a low density of load $T_{\max} \leqslant 4000$ h; (2) with an average density of load $4000 \leqslant T_{\max} \leqslant 7000$ h; (3) with a high density of load $7000 \leqslant T_{\max} \leqslant 8760$ h.

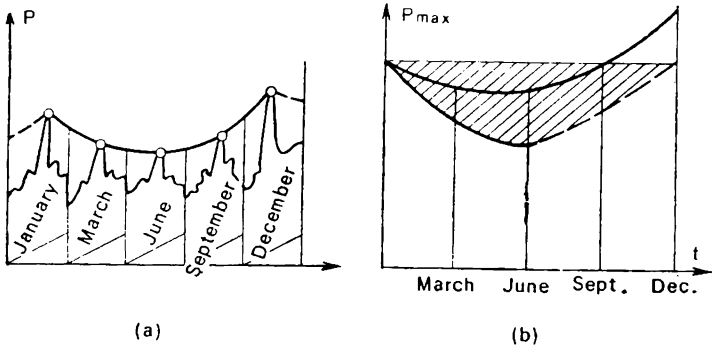

Fig. 1.2. Annual peak load curve
(*a*) spatial representation; (*b*) flat representation: without load increment (lower curve); with load increment (upper curve); load drop zone is shaded

There are typical load curves for these three types of the system which may be used for analyzing the system operation conditions if no more reliable data are available.

There may be two forms of assignment of the load curve in calculating the optimal conditions.

1. The load curve includes the resistive and reactive losses in the electric networks. The losses are determined as a certain fraction of the nodal load and are added to its useful load.

2. The load curve is plotted as a sum of useful loads with neglecting the electric network power losses.

The load curve representation affects to some extent the optimization results. For instance in the first case the sum of powers of the electric stations P_j should be equal to that by the load curve $\sum_j P_j = P$. In the second case, the load should exceed that by the load curve for the value of power losses π:

$$\sum_j P_j = P + \pi$$

If the network losses are strictly taken into account, which is usual for optimizing the conditions, the second representation of the load curve is used. However, this necessitates calculation of

the power losses at each stage of finding the optimal decision which is very time-consuming.

The curve representation with losses assumes that the losses determined before the distribution of load are independent of the distribution per se. Usually the losses are not regarded for in the power balance but are introduced as corrections to the differential characteristics of the electric power stations.

1.3. Power and Energy Balance

Active power balance. The active powers of the power and heat system are balanced at any instant of time. The power balance at time t has the form:

$$\sum_i P_{gen,\,i,\,t} = \sum_j P_{j,\,t} + \sum_l \pi_{l,\,t} \tag{1.5}$$

where $\sum_i P_{gen,i,t}$ = total power of the generators

$\sum_l \pi_{l,t}$ = total losses in the network and auxiliary power

$\sum_j P_{j,t}$ = total power consumption by the loads

Disturbances in the power balance lead to fluctuations of frequency, i.e. impair the quality of electric supply.

The power balance sheet of the system (pool) is compiled as shown below.

No.	Description
	Demand
1	Combined maximum of load
2	Transfer of power to other systems
3	Minimum reserve
4	Power losses
5	Total demand (1+2+3+4)
	Supply
6	Total installed power of electric stations
7	Non-usable power (interruptions or system restrictions)
8	Available power of electric stations (6—7)
9	Take-off from other systems
10	Total supply (8+9)
11	Excess (+) or shortage (—) of power (10—5)

The optimization process starts with drafting the power balance sheet. For the operation purposes such a sheet is compiled for each month or day. When planning the operation and the expansion of the power system, the power balance sheets are prepared for a

longer period (a year, five years). In the latter case the power balance sheet is compiled for the period of the annual load peak (which usually occurs in the last ten days of December). The power balance is frequently represented graphically (Fig. 1.3).

The power balance is complemented with the *energy balance* which defines the future consumption of fuel in the system and takes the form

$$\Sigma E_{gen,\ i} = \sum_j E_j + \sum_l \Delta E_l \qquad (1.6)$$

Reactive power balance. Likewise the active power, the reactive power of the power systems should also be balanced

$$\Sigma Q_{gen,i,t} + \Sigma Q_{com,t} + \Sigma Q_{tr,t} = \Sigma Q_t + \Sigma q_{l,t} \qquad (1.7)$$

where Q_{gen} = reactive power of the electric station generators
Q_{com} = power of the compensating devices (adjustable and non-adjustable)
Q_{tr} = charge power of the transmission lines
Q = reactive power of loads
q_l = reactive power losses

When the credit side (income) of the balance decreases, the electric network voltage drops and the active power losses usually increase. Therefore, the balance should be such as to maintain the permissible voltage levels at all the nodes. In addition to the checks of permissible voltage levels, planning the power system expansion involves a consideration of the economical feasibility of additional compensating devices (increase in the income side of the balance) if they will decrease power losses in the electric networks.

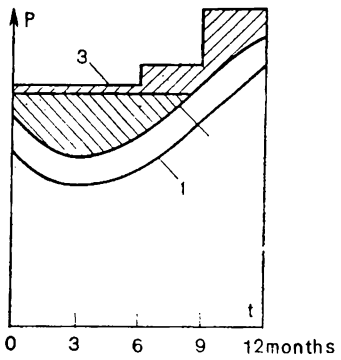

Fig. 1.3. System power balance
1—peak load curve; *2*—reserve power; *3*—system available power at non-uniform commitment

The main difference between the reactive power balance and the active one is that the excess of the reactive power in one part (region) of the power system cannot always compensate for power shortage in its other part. This is explained by that transmission of the reactive power over long distances is not always feasible or possible because of the rise or drop of the voltage level in the receiving portion of the system.

The reserves of the reactive power are provided at the nodes with particularly vital loads which impose stringent requirements on the voltage quality.

A high power factor of large turbine-generator sets, which considerably exceeds the natural power factor of the load nodes, and a high level of losses of the reactive power in transmission lines and transformers make it necessary to install additional reactive power sources. Each 1 kW of a newly implemented power requires usually from 0.9 to 1.2 kVAr of the reactive power of the additional sources.

1.4. Power Reserves

The power reserves are used to increase the reliability of electric power supplies. The total power reserve is comprised of the following types of reserves: load, emergency, maintenance, and

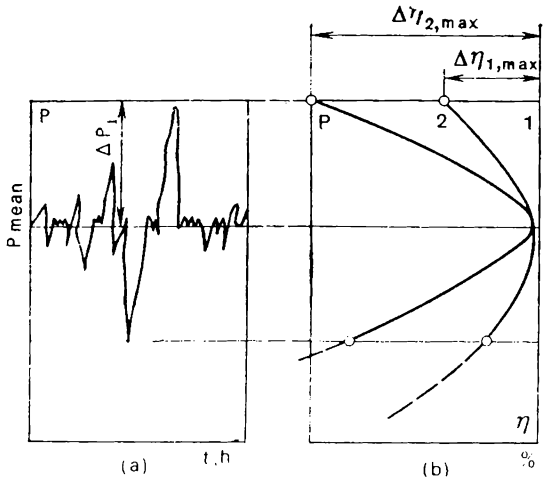

Fig. 1.4. Efficiency decrease at frequency regulation
(*a*) load variations; (*b*) variation range of regulating plant efficiency; *1* and *2*—regulating station characteristics

the economy reserves. The maintenance reserve is subdivided into the overhaul and routine reserves. Thus,

$$P_{res} = P_{ec} + P_l + P_{em} + P_{ov} + P_r \qquad (1.8)$$

The *load reserve* (1-3% of P_{inst}) serves for short-time supply of unplanned rises and occasional rushes of the load. Let us consider load variations of a system during a short time interval Δt (Fig. 1.4). Superpose it on the energy (equivalent) curve of the electric power station showing the relationship between the efficiency and power. This frequency-regulating station operates with an average load P_{av}. The reserve power of the station

$$P_l = P_{av} - P_{inst}$$

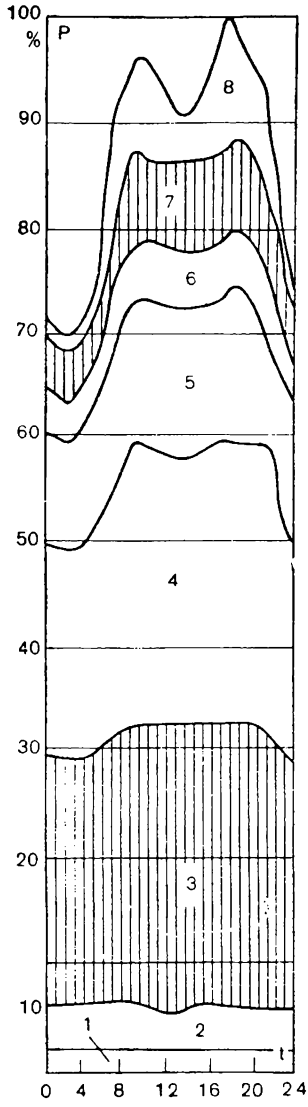

Fig. 1.5. Load supply diagrams
1—hydroelectric plant without regulation; *2*—nuclear power plant; *3*—thermoelectric plant; *4-6*—large unit condensation power plants; *7*—medium-pressure condensation power plants; *8*—regulating HPs and hydro-turbine uni's

The station takes up all the occasional load rushes. Therefore, an additional free power is necessary to regulate the frequency. Theoretically, this involves no additional energy consumption since the fuel rate is determined by the average load. However, if the load changes are great, the mean efficiency of the unit decreases and the energy losses occur caused by the frequency regulation (regulation losses). The steeper is the efficiency curve, the greater are the losses. The losses of the station with curve *2* exceed those of the station with curve *1*.

During low water periods, the hydroelectric station has a free power and can perform the frequency regulation functions. If the water level is high, the hydroelectric station operates at full power and cannot effect frequency regulation. In the systems which do not incorporate hydroelectric stations, the frequency is regulated by thermal stations which as a rule burn expensive fuel at a relatively high fuel rate. Such stations should be adapted to sharp fluctuations of load which also involves regulation losses.

The *emergency power reserve* (up to 10-12% of P_{inst}) is intended to compensate for outages. It is calculated by the probabilistic method on the assumption of the adopted reliability index of power supply or cost of supply lost. Selection of the optimal magnitude of the reserve is considered in the books devoted to the electric systems.

The emergency reserve should not be less than the power of the greatest unit of the system. From 40 to 60% of the emergency reserve is usually allocated to the hydroelectric station. The hydroelectric station in this case is equipped with a

device for automatic start of the hydraulic units in case of emergency decrease of frequency. The remaining part of the reserve is allocated to the thermal power station. If an accident leads to a long-term outage of the unit, a stand-by unit of the thermal power plant is started and the hydroelectric station is unloaded.

The emergency reserve somewhat impairs the optimal availability of the operating units and increases fuel rate.

The *overhaul power reserve* is established if the repair shop of the power and heat system does not allow repairing the equipment. The *routine maintenance reserve* is about 6% for the unit-type condensation stations and about 3% for the power and heat stations and condensation stations with lateral coupling without stand-by boilers of the entire installed power of the units of a given type. No special routine maintenance reserve is established for the hydraulic power stations since their power generating units are repaired during low-water periods.

The *economy reserve* is intended to supply probable unplanned consumption peaks and amounts to 1 or 2% of the maximum load.

System daily load supply. As it was mentioned above, the power balance should be ensured at any time of the day:

$$P_{av} = P_{op} + P_{res} \geqslant P_l + \pi + \Delta P_{aux}$$

where P_{av} = available power
P_{op} = operating power
P_{res} = reserve power
P_l = load power
P_{aux} = auxiliary (house) power

Let us consider the role of separate stations in the load supply of the system (Fig. 1.5). The large thermal units of the thermal power plants, hydroelectric stations without regulation, nuclear stations, and power and heat stations operate at the base line of the load curve; the average-size condensation power stations occupy the half-maximum zone, while the regulating hydroelectric stations and average-pressure thermal power plants are at the peak of the load curve. The load drop on Saturdays and Sundays necessitates disconnection of a part of the equipment. The load distribution between the stations cannot be arbitrary; it should be optimal to minimize the power production cost (fuel rate) in the system. The load distribution is greatly dependent on the characteristics and slewability of the units.

1.5. Dispatch Control

The power industry management involves management control, process control and on-line control. This book deals mainly with the on-line control. This type of control is frequently called a dis-

patch control since it is carried out by a special dispatch service. This service relies in its operation on a network of dispatch points (centers). The dispatch control service of the power production was established in the USSR in mid 1920's.

Dispatch control is a centralized and continuous control of the power and heat system operation carried out by the top executive called dispatcher. A successful operation of the dispatch control center requires the use of special facilities to inform the dispatcher of the status of the power and heat system being controlled. In early days of the dispatch control, simple control boards and conventional communication means (telephone) were used for the purpose. Later appeared the telemechanic equipment which automatically displayed the status of the switching gear on a special board and measured the basic variables. Next the dispatch control points were equipped with devices for automatic frequency control, power exchange and load distribution.

The growth of the information body at a limited time available for its processing necessitated complementing the traditional dispatch control facilities with modern computers; later the automatic dispatch control systems ADCS and branch management control system Energiya were implemented.

Power industry control hierarchy. The dispatch control is executed according to the hierarchical principle. In the USSR, the on-line control includes four sufficiently independent control levels (control ranks): electric power station—power system (production merger)—area-level control board (ACB)—central control department of the USSR power grid (USSR PG CCD).*

Such an hierarchy is often called *spatial hierarchy* (the greater is the territory covered by the control, the higher is the control rank). In addition to the spatial hierarchy, there are distinguished a *temporal hierarchy* and a *situational hierarchy*. The temporal hierarchy is needed to use different time periods in planning the expansion and operation of the power system. Usually three temporal levels are distinguished: operation planning, on-line control ensuring the planned operating conditions, automatic control with the aid of the appropriate automatic devices. The operation planning is in turn subdivided into several levels: long-term planning (10-20 years, five-year period), routine planning (year, quarter, month) and on-line (real-time) planning (day, ten days).

The situation hierarchy distinguishes between three control ranks: normal, post-emergency and emergency control. This book deals with the problems of optimization of the normal operation.

Tasks of dispatch control. The principal task of the dispatch control is to program the operation of the power system and to execute

* For the acronyms used in the text see p. 10.

it properly. The system should ensure troublefree and continuous electric power supply at a standard quality of power and minimum production cost. The search and embodiment of such operating conditions will be referred to as the optimization of the power system operation.

The power industry management problems are diverse. They include:

—automatic control of frequency and active power and restriction of energy transfer via the transmission lines;
—automatic regulation of voltage and reactive power;
—daily additional optimization and correction of load distribution;
—analysis of deviations from the planned conditions;
—urgent forecast of the daily load curves of the power systems and network nodes in the interests of the on-line control;
—proximate calculations of the normal operation of the electric network, static and dynamic stability;
—keeping of the dispatch control documents, etc.

Most of these are complex optimization problems which are solved with an intensive use of computers. The same problems are included in the sphere of the management control systems at different levels.

Control of power system operation and controlled variables. The performance of a power system can be changed by two methods:

(1) disconnection (connection) of any element of the system, i.e. a generator, a transmission line, a transformer, a reactive power source, a regulating load;

(2) change of some operation variables, i.e. power resource consumption, its energy potential, power, voltage, etc.

The first method will be hereinafter referred to as a choice of a rational availability (allocation) of the system elements, or merely the availability choice, and the second method a choice of operation variables. The both methods are frequently used when optimizing operation of the power systems.

The performance of the power system with a constant availability can be changed by varying:

—the active power of the generating units;
—the reactive power of the generating units;
—the transformation ratios of the variable-ratio transformers.

These values will be referred to as *controlled variables*. The nodal load may be changed within a narrow range by changing the nodal voltage through varying the transformation ratios or the reactive load. This method is applicable only in emergency or under the post-emergency conditions. No other methods for controlling the system operation are known today. The ranges of changing the controlled variables and the possibilities of altering the availability are limited by the available power of the generating unit,

the system or network power balance, the transmission line capacity, nodal voltage levels, power supply stability and reliability.

Prior to considering separate problems of optimization, let us review the fundamentals of the theory of mathematical modeling of operating conditions and the principles of construction of the Energiya branch management control system.

2

MANAGEMENT AND/OR CONTROL SYSTEMS IN THE POWER INDUSTRY

2.1. General Principles of Implementing MCS in the Power Industry

Basic definitions. Before proceeding to the concept of the management and control we shall define the terms related to this concept. A *system* is an assemblage of interrelated components to perform a common task. In other words, the system is, in a sense, a closed entity. This best applies to engineering systems and they will be the subject of our discussion.

A *control system* combines various automatic devices which sense pertinent variables with some functions being performed by man. The term "automatic" always includes the participation of man. Quite aptly we call it a man-machine, or ergotic system.

The *management control* may be defined as a purposeful action upon an object or a process to evoke qualitative and quantitative changes of its variables with a view to achieving a particular goal.

Thus, MCS is a man-machine system capable of perceiving, storing and processing information for the purposes of optimum control in various spheres of human activities. In optimizing one strives to minimize or maximize the objective function.

By analogy, the term management and/or control system for a power plant, power system, an interconnected power system or pool* will refer to a man-machine system ensuring automatic perceiving, storing and processing of data required to optimize expansion and operation at the respective level. The power plant management control system (PP MCS) should be adapted for operating both separately and within the framework of a power system MCS (PS MCS).

Classification of MCSs. We have two classes of management and/or control systems: management information systems and process control systems. The management information system, as its name implies, handles managerial decision making with the personnel included. Process control is the control of plant and machinery. The former has to do with men, the latter with plant, machinery and processes. Another difference is the form in which information is transmitted. In the first case this is done by documents, in the second, by various signals.

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* IS MCS.

In fact, modern systems combine both management and control functions but they may be predominately management-oriented or predominately process control-oriented.

Such systems may be called integrated or comprehensive (PP MCS and PS MCS are integrated systems).

There are different methods of information input/output: manual data input and generation of recommendations (manual control), automatic input of data and generation of recommendations, automatic input of data and automatic supply of control signals to the plant (process) or a direct numerical control. The first two cases are advisory machine stages, the third case is characteristic of automatic process control systems (APCS). The second and third cases require special devices for connecting the computer to the plant.

MCSs may be conventionally divided into search, advisory and control systems. By a *search system* is usually meant one which is intended for a systematic examination of the available information in a specific field of interest. The search is effected by a request which describes the classification of the object properties in the encoded form. Such systems are used for bibliographic search, search for a required file, descriptions of prior art machines, a list of patents according to the request or code, etc. As for the PP MCS its functions are to answer the questions of a dispatcher (an engineer on duty). The dispatcher may take his requests from some pre-compiled lists where each request is assigned a certain number (name). On receiving a request, MCS prints it or displays on a cathode-ray tube screen with indicating the data required to be loaded. The input data are checked and in case of an error MCS requests necessary corrections. After processing the loaded data MCS presents the required information.

The *advisory system* is used for routine control in PP MCS. It furnishes the managers with the information showing deviations from the work schedule. This provides for updating the schedule or, if the deviations are excessive, for developing a new plan. The advisory system determines the possibility of speeding up or improving the production process at each (even short) period of time and relays the information to the power station operator.

If the operator does not follow the advice, MCS should begin accumulating the data on the energy resource losses caused by ignoring the advice and print out these data by the end of the shift with indicating the cause of the losses. If the process is in full compliance with the program and there are no ways for improvements, the advisory system should display no information except the data needed for statistical purposes and upkeeping files which are automatically accumulated in MCS without any participation of the operator.

The *control system* solves the same problems as the advisory

system does, but some of the recommendations are generated as signals for immediate control of certain process equipment (starting and stopping of units, frequency control, power exchange, etc.).

Basics of methodology, construction and operation of MCS. The economic advisability is one of the vital principles of the MCS methodology. MCSs are advisable in large power systems where they offer the maximum effectiveness. The best results are obtained when optimization tasks are solved, e.g. drawing up optimal daily or monthly operating schedules for the power systems.

The principle of unification of MCS shows the trend for the maximum use of standard solutions. Separate PP MCS or PS MCS subsystems may be designed on the basis of the typical tasks. The components of the MCS equipment are also subject to unification. This principle cuts the costs and accelerates the implementation of MCS.

The principle of systems approach requires that PP MCS be created after a complex of organizational, methodological and technological measures having been taken. It is necessary to choose grounded and definite criteria for evaluating operation of separate subunits. Implementation of MCS may alter the organizational structure, responsibilities of various elements of management, documentation, and the established information flows.

The existing power generating equipment is often unsuitable for cybernetic systems and has an inadequate control system so that the equipment and its control system have to be modernized to implement MCS. The systems approach is aimed at solving these and some other problems.

The continuity of methodology implies that the basic concepts are identical so that MCSs of different levels can be unified and integrated into a single management and/or control system for the entire branch—BMCS ENERGIYA. The principle of proper hierarchy in management requires the participation of the manager or chief engineer of the power plant (PP) in the development of MCSs since their implementation involves radical changes in the concepts of management. The principle of computerized handling of documents refers to the fact that primary documents are loaded into a computer directly and only once, without collation and merger, with their preparation and loading overlapped. When designing information flows in MCS, it is possible to use a secondary (output) document as a basis for the synthesis of the primary flows. Such an approach is sometimes referred to as the principle of priority of the secondary document.

Analysis and synthesis in construction of PP MCS. PP MCS may be implemented in the existing power station or be designed and developed concurrently with the latter. In the first case the basic parameters of the power station, its equipment and operating conditions are defined and MCS becomes a superstructure on the already

formed management system. In the second case, when PP and MCS are designed simultaneously, the management control system may to some extent affect the parameters of the station, its equipment, local control devices, management structure and operation reliability. The first case will be referred to as analysis, the second, synthesis. The synthesis is far more effective though imposing more stringent requirements to the speed of response and reliability of MCS. The attention of this book is focused on the operation principles of MCS created on the analysis principle since the methods of joint designing of MCS and PP have not yet been thoroughly elaborated.

Outline presentation of MCS. MCSs of different classes may be represented as consisting of six subsystems performing different functions. These include hardware of MCS, software consisting of algorithms and utilities for MCS, information support (a system and rules for data collecting, storing and processing); organizational-methodological support, manpower support and legal support.

The first three subsystems will be considered below at a sufficient length. The *legal support* is a system of legislative acts and instructions to regulate the work of the MCS personnel. It establishes a particular procedure and legal aspects of formalizing the machine documents, responsibility for retention of data and non-observance of the computer advices, forbidding of access to some classified information, etc.

The *methodological support* is a system of guiding documents and instructions to ensure the compatibility of MCSs of different types and levels for subsequently integrating them into a single system.

The *manpower support*. The term will refer to the trained specialists needed for normal functioning of MCS.

2.2. MCS Structure

Functional MCSs. Before the advent of MCSs, the management was carried out on a functional basis. The factory, or its equivalent (in an industry) had management subunits (departments) which performed particular functions (Fig. 2.1*a*). The first MCSs repeated the established management structure and were superstructures to it. Such MCS (Fig. 2.1*b*) called functional MCS (dedicated management information systems) may be represented as consisting of a number of functional subsystems aiding the personnel of the respective management subunits to perform their main functions.

Each subsystem handled tasks to be solved by a given management subunit. The information for such tasks was prepared (often manually) by the respective management subunit with the help from the MCS operators allocated to the given subsystem. Such MCSs mecha-

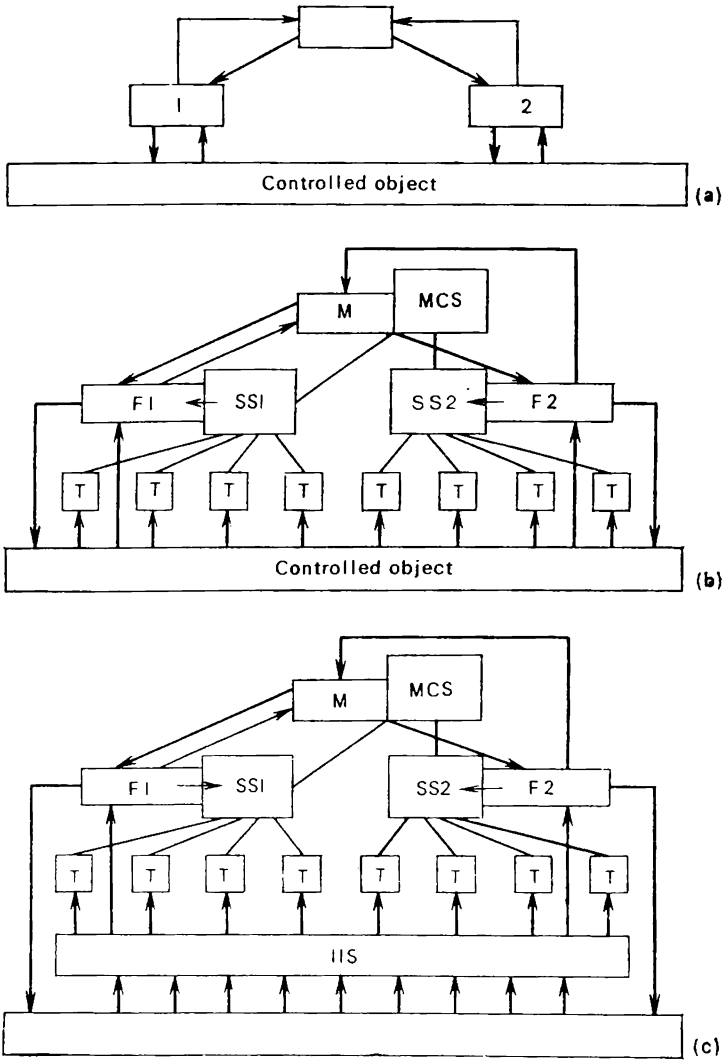

Fig. 2.1. MCS structure

(*a*) functional control (management); (*b*) functional MCS without integrated information system (IIS); (*c*) ditto with integrated information system; *M*—manager; *F*—functional (management) subunit; *SS*—MCS subsystem; *T*—SS task; thick lines show management links, thin lines, information links

nized routine procedures for collecting information, solved some new tasks that could not be coped with before because of the lack of information or the complicacy of calculations. In traditional management and control, various departments duplicated the functions of the respective management and/or control systems and

backed them in case of computer failure. The latter function was very important at early days of MCS when the hardware was far from perfection.

The old information retrieval system could not cope with new and more complex tasks. The data collected by different subsystems using different methods were sometimes conflicting or incompatible. The mechanization of routine problems failed to yield good results. The allocation of functions among the personnel of the functional services and MCS operators was vague. All the above have led to the advent of new management control systems—MCS with integrated information systems (Fig. 2.1*c*). The plant is again under the control of the respective departments. The MCS structure has not been radically changed. However, all the MCS tasks are handled with the use of a single information source—a common data bank or integrated data processing system (IDPS). All the initial data are correlated, so that they do not conflict any more. The information communications are considerably simplified. The information retrieval time is shortened. The initial data are loaded into MCS only once and for all the tasks.

Most MCSs today are constructed in such a form, branch MCS ENERGIYA including. However, in this case the existing functional services cannot fully back up MCS in case of its failure since they have no information channels. If the computer fails, the data bank becomes inoperative and the management effectiveness drastically decreases. Therefore, particularly stringent requirements should be imposed on the reliability of such MCSs.

Thus, functional MCS comprises sufficiently independent subsystems. Each subsystem handles a certain number of problems interconnected by a common integrated information system. The composition of the subsystems and problems determines the MCS structure.

Task. The task is a complex of algorithms grouped, e.g. for convenience in forming the initial data, variables or output documents. The set of tasks defines the MCS capacity. The task may be regarded as a certain final module which is used for making a decision or determining one summary variable. The set of tasks determines a certain language of MCS.

MCSs are sometimes considered in terms of a scope of tasks handled:

$$Y_{pr} = \frac{mn}{Mn_{\max}} \tag{2.1}$$

where m is the number of the subunits of the factory covered by MCS; M is the total number of subunits; n is the number of tasks handled by MCS at a given subunit and $n_{\max}$ is the total number of tasks. It is assumed that in power system MCS $n_{\max} = 150\text{-}200$ tasks.

MCS structure and parameters. For convenience in comparison of the structures of different functional MCSs, they may be represented by the following formula

$$\sum_i n_i T_i - A(f-j) + \sum_k n_k T_k \qquad (2.2)$$

where n and T are the number and type of machines, respectively; A is the MCS type which is defined as follows: B—branch MCS, F—factory MCS, P—process MCS, G—MCS of a group of enterprises, T—total (integrated) MCS, etc.; f and j are the numbers of the subsystems and problems, respectively. The sign "+" indicates the number and types of machines controlled directly in a given MCS, for instance:

2M-7000—T(4-17)+M-6000

This designation means that a two-level total MCS whose hardware includes two computers M-7000 (upper level) and one subordinate computer M-6000, comprises four subsystems solving 17 problems.

Support subsystems. In addition to the above-listed functional subsystems, MCS includes subsystems which are common for all the functional subsystems. Among these are an information subsystem, a software subsystem, etc. Such subsystems are called support ones.

MCS hierarchy. Main types of MCSs. In the USSR MCSs are arranged according to a hierarchic principle. There are two kinds of MCS hierarchy: one covering individual industries (branches) and the other covering particular regions. We shall regard the branch hierarchy of MCS. The lower level of MCS (Fig. 2.2) is the automatic process control systems APCS. This level is usually considered null. The first level is represented by factory MCS (FMCS), the second level, by pool MCS (IS MCS), the third by branch MCS (BMCS). The top level is all-union (national) MCS (USSR NMCS) which manages the whole country. The structure of FMCS—IS MCS—BMCS corresponds to the three-element branch management control system.

Branch management control system ENERGIYA. The ENERGIYA BMCS is created to control the construction and operation of power systems. This system is a combination of mathematical, economic and administrative methods realized on the basis of modern computer, managerial, and information facilities which ensures the most efficient management of the power industry as a branch of the national economy of the whole country. BMCS is organized as a single system for managing the production, distribution and sale of electric power and heat energy, as well as managing the capital construction and industrial factories.

MCS subsystems. ENERGIYA BMCS comprises two special, nine functional and a number of general support subsystems (Fig. 2.3).

The first special subsystem is intended to manage capital construction and industrial factories (CMCS). This subsystem is beyond

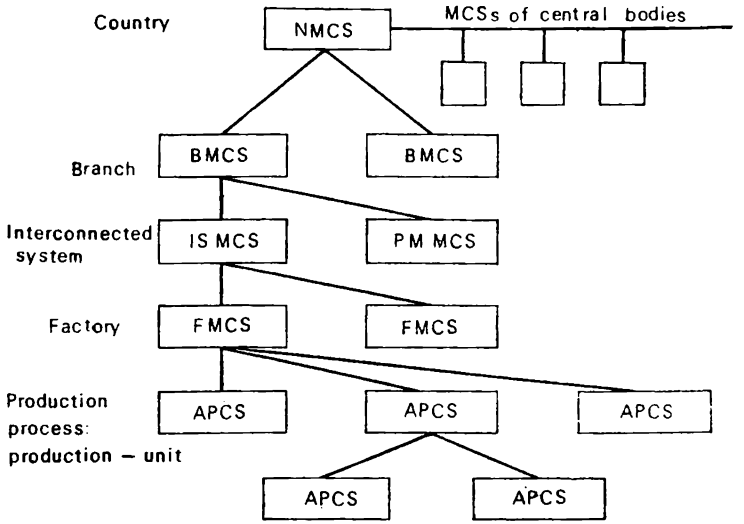

Fig. 2.2. MSC hierarchy in the USSR

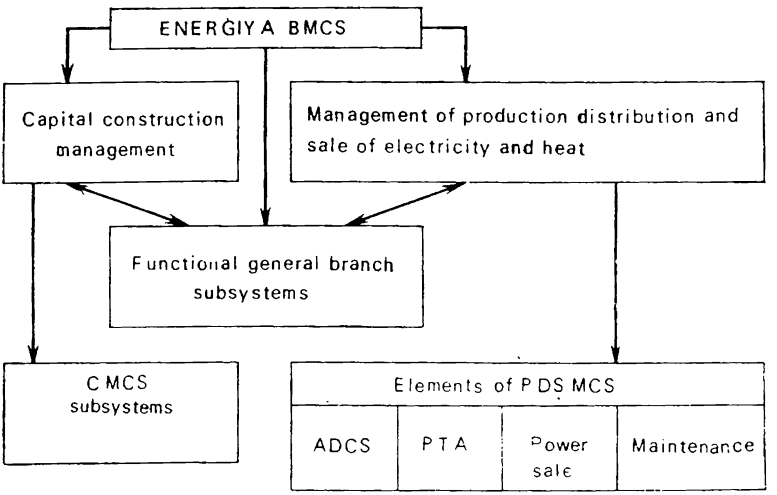

Fig. 2.3. Structure of ENERGIYA BMCS

our discussion. The second special subsystem is used to manage the production, distribution and sale of electric power and heat energy (PDS MCS).

Functional subsystems. The functional subsystems serve the top level MCS—MCS of the USSR Ministry of Power Industry. They are nine in all. They are of a type-design (general-branch) and manage:

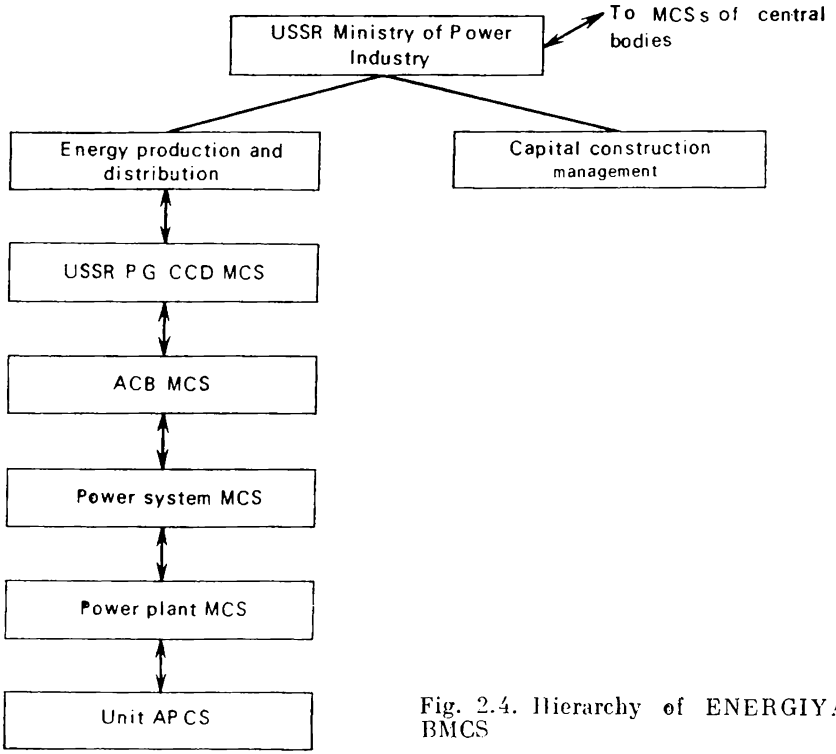

Fig. 2.4. Hierarchy of ENERGIYA BMCS

(1) long-term development of the branch;
(2) technical-and-economic planning;
(3) finance;
(4) planning, accounting and analysis of labour and wages;
(5) logistics and supplies. This includes the management of materials, products and structures, process equipment, building materials, fuel;
(6) planning, accounting and analysis of personnel;
(7) scientific, research and design work and scientific and technical information;
(8) accountancy;
(9) transport and centralized haulage. This includes the technical-and-economic planning of transport and analysis of the organization activity and centralized haulage, on-line control of haulage.

Sometimes the combination of the functional subsystems is considered to be independent MCS for the organizational and economic management performing the functions of the third component of the ENERGIYA BMCS.

Hierarchy of the ENERGIYA BMCS. The ENERGIYA BMCS is a multi-level system (Fig. 2.4). The zero level in subsystem PDS MCS corresponds to APCS of the electric power station (power generating unit), the first level is the power system MCS, the second level is intended for the dispatch control (service) (ACB level), the third level is the branch level (USSR PG CCD). The complexity of the management structure, its separation into the dispatch control and economic management complicate and somewhat change the typical pattern but can be adapted for implementing various types of MCS.

2.3. Structure of PDS MCS Subsystems

The electric power and heat energy production, distribution and sale MCS comprises four elements (Fig. 2.3): automatic dispatch control system (ADCS), production and technical activity (PTA), maintenance control (MMCS), sale management (SMCS), i.e. PDS MCS = ADCS MCS + PTA MCS + MMCS + SMCS.

Let us briefly discuss the first three elements.

The element of automatic dispatch control system (ADCS). The ADCS element handles the tasks of information, automatic frequency control, active power regulation, power transfers via the transmission lines, twenty-four hour optimization and updating of the power system operation, routine planning, etc.

Creation of ADCS is a complex multi-stage process. The experience gained in operation of the first phase of ADCS makes it possible to develop the second phase which is under way at present. The routine (long-term) planning involves the development and correction of long-term operation of the hydro power station cascades, overhaul repair plans, fuel supply plans, power generation and fuel rate plans, the analysis of accomplishment of the plans, etc. The short-term planning involves the development of the daily and weekly resistive load curves, optimal distribution of load, processing of requests for routine maintenance. The calculations for routine correction of the daily performance are carried out and the emergency repair requests are satisfied in the interests of the routine management. The correction is used to check if the electric network operating conditions are inside the permissible limits.

We review now the tasks solved by other elements of PDS MCS.

The element of production and technical activity (PTA MCS). The PTA MCS section is used for rating, long-term and routine planning, and statistical accounting and analysis. The PTA elements

should control the main technical-and-economic indices (TEI) of the basic production. The element should be considered jointly with other functional subsystems of the ENERGIYA BMCS: logistics, planning, accounting and analysis of personnel, accountancy, transport and centralized haulage, finance, etc. These subsystems involve the respective tasks of the element.

The PTA element is linked with ADCS. It carries out the routine analysis of TEI from data of the real-time information, participates in routine planning, performs statistical accounting of the production and economic factors affecting the plan. The element is also linked with the long-term planning subsystem to relay the past period information to it.

The element manages:

— the supply of electric power and heat energy produced by big stations, separate power generating units of the regional power departments;

— the consumption of equivalent (natural) fuel for the production and supply of electric power and heat energy;

—the utilization factors of the installed power;

—losses in the network and consumption of power and heat for house requirements;

—the exchange of power between systems and pools and of purchased power; export and import of electricity;

—the production cost and profit.

The element simplifies preparation of the proposals for compiling and correcting the quarterly and annual plans (e.g. of fuel rates); annual accounts; proposals for improving the equipment economy, modernizing and discarding the obsolete equipment; proposals for compiling annual and quarterly plans of fuel supplies to the regional power departments and large stations.

To execute these functions, it is necessary to automate the present-day, monthly, quarterly and annual control and accounting of the main technical-and-economic indices (TEI) of the power systems and pools, statistical research of TEIs for making real-time management decisions.

Subject to automation should be:

—compilation and analysis of summary statistical reports on operation of the thermal and hydro power stations;

—collection and analysis (verification) of the monthly technical-and-economic indices of the power system operation;

—accounting of TEIs for a month, quarter, or year;

—registration of main indices of production cost for the pool and the power system;

—accounting of quarterly (monthly) power and heat supply plans;

—compilation of statistical reports for a month or ten-day period.

The algorithms and programs of annual planning of fuel supply

to the power stations (with break-down to quarters) are being worked out with the provision for quarterly and monthly updating.

Maintenance control element (MMCS). Striving for reducing the terms and costs of repairs with the simultaneous improvement of repair quality has led to implementing the maintenance MCS and to creating the maintenance control element.

The most important tasks handled by the MMCS element are as follows:

1. Routine supervision of accomplishment of the medium and overhaul repair plans.
2. The information-reference system on the availability of the vital spares for the standard equipment.
3. Routine supervision of allocation, use and reconditioning of the centralized spare stock.
4. Calculation of optimum ratings for the centralized spare stock.
5. A data file on machine media containing information on the equipment of all the power stations of the USSR Ministry of Power Industry.
6. The system for retrieval and processing of information on the reliability of power stations and networks.
7. Planning of complex overhaul repairs of transmission lines.
8. Optimization of terms and volumes of transmission line maintenance and repairs.
9. Optimization of maintenance and repairs of the network transformers.
10. Optimization of maintenance and repairs of switching gear and insulation of the substations.
11. Calculation of the quantity and locations of the specialized travelling teams for repair of the basic equipment of the power stations and substations.
12. Organization of routine servicing of distribution networks.
13. Planning of labour input and expenses for repairs.

3

MCS HARDWARE AND SOFTWARE COMPONENTS

3.1. MCS Computers

Computer systems. Two systems of computers are presently used for MCS: a unified system of electronic computers (USC) and a modular (building block) computer system (BBCS). The former is employed in the power industry mainly for planning tasks and the latter, for process control.

Unified system of electronic computers (USC). The third generation computers are organized on the "central processor and other devices" principle. The basis of the computer system is a processor coupled by internal links with the temporary storage. The peripheral units (PU) are connected to the processor (Fig. 3.1*b*). The PU set depends on the MCS tasks. The peripherals are coupled via special exchange devices called channels. Connection to the channels is performed with the aid of a standard interface unit. All the devices (modules) have standard interfaces which are constructionally a multicontact detachable cable connector (joint). Uniform groups of peripheral units are connected to the channels via control units (CU), or controllers.

The processor makes the backbone of the computer. It performs logic and arithmetic operations, controls the computational process and coordinates the operation of the peripheral units of the computer. The processor is characterized by an average speed of response which is usually measured in thousands of operations per second. The information is admitted to the processor only through the *temporary storage* (TS). TS stores a working routine (or its part), intermediate and final results.

The temporary storage is characterized by the access rate and memory capacity. The capacity is measured in kilobytes. One kilobyte is equal to 1000 of eight-digit bits (sometimes, 1024 bits are indicated as Kbyte). Constructionally the temporary storage devices are usually made on ferrite elements. In the last few years semiconductor temporary storage devices have been introduced. There are erasable and read-only storage units. The read-only storage, as its name implies, prohibits new entries. Such devices are usually used for storing standard routines.

The channels are intended to link the peripheral (external) units to the computer. Two types of channels are distinguished: a selector channel (high-speed) and a multiplexor channel (low-speed).

The *selector channel* (SC) is used for connecting high-speed peripheral units to the processor. These are magnetic tape, magnetic disk (permanently-mounted or removable), storage screens or displays.

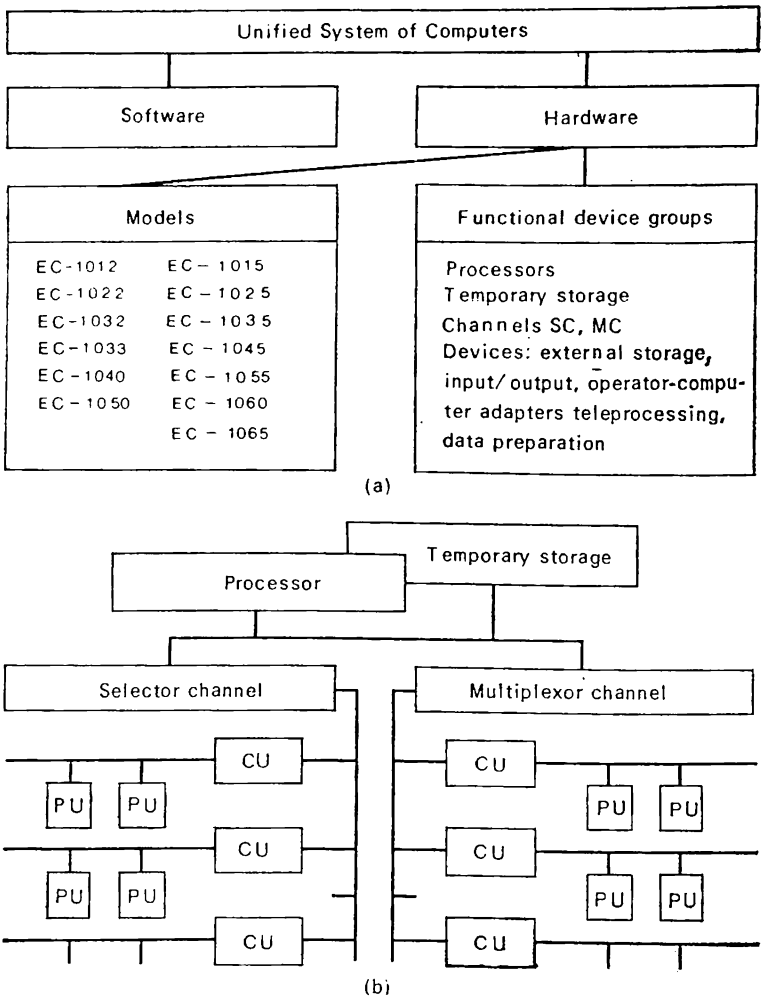

Fig. 3.1. Principal components of computer

(*a*) components; (*b*) structure of unified system computer; *PU*—peripheral unit; *CU*—control unit; *EC*—unified system

The unified system machines of different types may include several selector channels operating independently: in the first models up to two and in the later ones up to six channels. Each channel operates with only one peripheral device at every instant. The selector

channel may be used for multi-computer organization through a special adapter unit.

The *multiplexor channel* (MC) ensures a simultaneous data exchange with several peripherals operating at a relatively low or medium speed. These are punched cards and tape printers, data teleprocessing devices. Up to eight control units can be connected to the multiplexor channel of USC (up to 10 to the EC*-1040 channel) and several peripherals (usually up to 8) can be connected to each control unit. The multiplexor channel may include several selector subchannels to exchange data with one of the peripherals in the burst mode which increases the rate of exchange.

Components of *peripheral units*. The components of the peripheral units of all the computers belonging to the unified system are similar. There are five groups of such units (Fig. 3.1*a*): external storage, data display devices (operator peripherals), communication devices (data teleprocessing equipment), data input/output devices, data preparation facilities.

The *external storage* is used to hold vast files of rarely used data. There are direct-access (random-access) and sequential-access storage devices. The example of the first type of storage is magnetic-disk units which provide access to the location directly independent of the location of the information most recently obtained. The example of the sequential-access storage is the magnetic tape in which the items of information stored become available only in a one after the other sequence. The direct-access storage offers a higher speed of response. The data hold in the external storage must be transferred to the internal temporary storage prior to processing. This operation is called *storage exchange* and is carried out by the channel processor on the instruction from the central processor. Usually exchanged are data files. In some computers the exchange step is carried out simultaneously with the operation of the central processor which may solve another problem at this time. Such a mode is termed a direct access mode.

The information is input into the computer from the punched cards, punched tapes or from magnetic tape and is output on punched cards and punched tapes. The input speed is 600 punched cards per minute or 300-1500 lines per minute (for punched tapes), the output speed is 100-250 punched cards (100-200 lines) per minute. The alphanumerical information may be input through the screen keyboard and output to the printers and displays.

The *printers* are usually divided into serial (character at a time) printers having a speed of 10 characters per second and line printers which print one line of characters at a time. The latter include numerical narrow tape printers and alphanumeric wide tape printers

* EC—Russian abbreviation for unified system.

(ANP). The wide tape has the width of a double standard sheet of writing paper (128-character line). The printing speed reaches 600-1200 lines per minute.

Data displays. The data displays are devices for visual representation of data. These devices are necessary for the operator (engineer on duty) which controls the modes of the power station operation. The display screens may represent alphanumerical and graphic information, calculation results, instructions, drawings, diagrams. The alphanumerical information may be edited on the display console by inserting symbols, words or phrases, erasing and text linking. The displays simplify the input/output of data, thus simplifying a most difficult junction: man-machine.

There are two types of displays. The relatively simple *alphanumerical displays* provide for visually displaying alphanumerical information and projecting some simple images similar to those that can be typed on a typewriter. The *graphic information display* permits insertion and editing of graphic images—drawings and diagrams. The graphic information is edited with the use of a light pen. When using the light pen, the place on the screen where editorial correcting should be made may be marked by the operator with a special marker (tracking cross). As the marker is illuminated with the light pen, the computer automatically tracks the light pen so that the cross is always in the center of the pen field. As the light pen is slowly moved along the screen, the tracking cross follows it and the coordinates of the line being traced are input in the storage.

The light pen is employed for depicting relatively simple patterns. To represent frequently used symbols, special function push buttons are used. The image of the symbol precoded and written in the memory is displayed on the screen by pushing the respective button. The graphic information can be input with the aid of a special input device similar to that utilized in facsimile. The punched cards can be also used for inserting information by describing a graphic drawing in a special graphic language. The languages for describing flat (two-dimensional) drawings have received the most development.

Multisystem properties. USC is so constructed that the computers may be combined into multiprocessor and multisystem computer complexes. The connections between the processors may be organized at three levels:

(1) the use of a common external memory (tapes, disks): this is the slowest but the simplest connection of the machines;

(2) the direct connection between the channels of two computers; this method requires the use of a special channel connector;

(3) the sharing of the temporary storage between two processes. In this case the direct control means are employed for transmitting signals from one processor to the other.

Table 3.1

Basic Specifications of Some Models of EC Computers and of M-4030 Computer

Characteristics	Computer type							
	EC-1022	EC-1032	EC-1033	EC-1035	EC-1040	EC-1050	EC-1060	M-4030
Average operation time, μs:								
fixed-point addition	3.3-6.0	2.4	1.4-2.7	2-4	1.4-2.0	0.65	0.32	6.25*
floating-point addition	14-18	4.1	4.5	6-11	2.5-3.6	1.4	1.80	13.5
fixed-point multiplication	29-32	16.4	8.5	20-30	1.2-8.2	2	1.55	18.2
floating-point multiplication	39-42	12.9	9.5	16-48	6.5-13.1	2	2.85	—
fixed-point division	65-68	17.3	14.6	30-36	6.5-13.1	2	5.75	—
floating-point division	60	13.2	17.7	28-32	18.1	7.2	4.40	—
short operations	3.3-6.0	2.4	1.4-2.7	5.5	1.4-2.0	0.65	0.32	3.5
Speed of response, thousand operations per second	80		220		380	500		100
Temporary storage capacity, Kbyte	256-512	128-1024	256-572 to 1024	256-572 to 1024	256-512	256-1024	2048/8196	128-512
Multiplexor channel: number of channels/subchannels	1/128	1/256	1/32	1/16-128	1/128	1/192	2/192	1/184
data transmission speed (multiplexor mode/burst mode), Kbyte/s	80/400	145/457	50/300	40/130	25/180-120	30-110/100-180	110/670	50/140
Number of selector channels/transmission speed, Kbyte/s	2/700	3/1100	3/800	4/140	6/1300	8/130	6/1250	3/1000
Power consumption, kVA	25	23	40	41	65	70	100	25
Required floor area, m^2	108	80	120	110	150	200-250	270	110
Price, thousand roubles	387	—	600	—	—	1400	—	
Manufacturer	USSR, Bulgaria	Poland	USSR	USSR	GDR	USSR	USSR	USSR

* The time of operations upon 32-bit words. The speed of response of the computer is constantly increasing.

The first and second types of connection are most frequently used in PP MCS.

We now consider some computers of the unified system (Table 3.1).

Computer EC-1012 has been developed in Hungary and is manufactured at the "Videoton" factory. It is a junior model of the unified

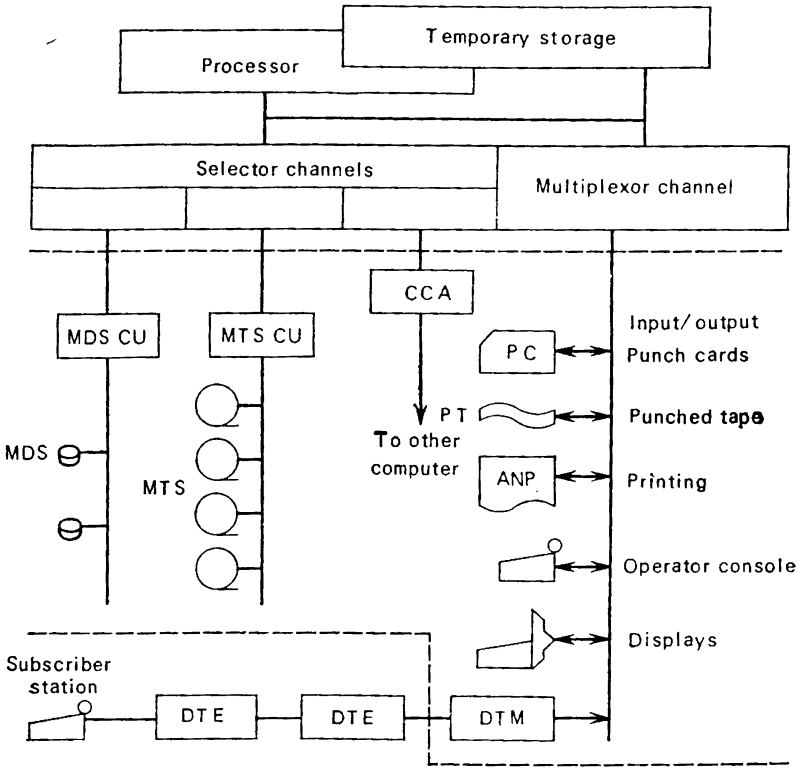

Fig. 3.2. Block diagram of EC-1022 computer

DTE—data transmission equipment; *DTM*—data transmission multiplexor; *MDS*—magnetic disc storage; *MTS*—magnetic tape storage; *CCA*—channel connector

system. The machine features a microprogram control and an efficient set of instructions, convenient control of the peripheral units, modern set of these units. The computer can be used in combination with other computers of the system. It has positive debugging system and modern software. The EC-1012 computer does not include functionally separate communication channels. The peripheral units are connected directly to the processor. It is allowed to attach up to 127 units.

The computer can be used in scientific and engineering calculations, warehouse stock accounting, collection of measurement data,

monitoring and control of production processes, computer-aided instructions. It can operate as a programmed control unit (subscriber station) or as an auxiliary machine for a more powerful computer (e.g. EC-1033) by controlling the external memory (the connection is established through the disks used by both machines simultaneously). However, the system of instructions of the EC-1012 computer is different from those of other computers.

Computer EC-1022 (Fig. 3.2) is manufactured in Bulgaria and in the USSR on the basis of the same documentation. It has a temporary storage of from 256 to 512 Kbytes, the external storage devices (up to 8 in all) on replaceable magnetic disks and on a magnetic tape. The output data may be fed to the AN printer; the operator console is provided with a typewriter. The multiplexor channel allows for connecting from 48 to 128 subchannels. The computer may include up to 2 selector channels and up to 8 control units.

Other machines of the unified system differ primarily in the increased speed of response, temporary storage capacity and standard equipment.

3.2. USC Software

Storage organization. The computers have a byte-organized storage. Byte is a 8-bit group. The other formats are divisible by this value: a half-word is equal to 2 bytes, a word is equal to 4 bytes and a double-word to 8 bytes. The total set of instructions includes 143 operations for performing fixed- and floating-point calculations, decimal and variable-length field operations. The set of instructions is universal; it offers the efficient and convenient means for computerizing the PP and PS management.

US computer modes of operation. A single-program mode in which the machine solves only one task is tolerable but is seldom used because of low efficiency. The multiprogram mode when the computer solves several tasks at a time is employed more frequently. Such a mode permits a sequential solving of the entire package of tasks and is called package processing mode. The task is solved simultaneously with the input of the succeeding task and with the output of the preceding tasks results. The *time-sharing* is a more complex mode since the computer serves several subscribers at a time (including remote stations) using a priority system to choose the sequence of solving. The computer can operate in the real-time for controlling the production process. The different modes are ensured by the operating system of the computer.

USC general software structure. The software (Fig. 3.3) comprises the operating system (OS), a set of maintenance routines (debugging and diagnostic tests) and utility packages (UP).

The operating system automates the operation processes of the computer. It increases the machine efficiency, ensures different modes of computing system operation, automatic input of tasks, overlapping of the input of a new task with the output of the previously solved ones, a multiprogram mode of operation with the

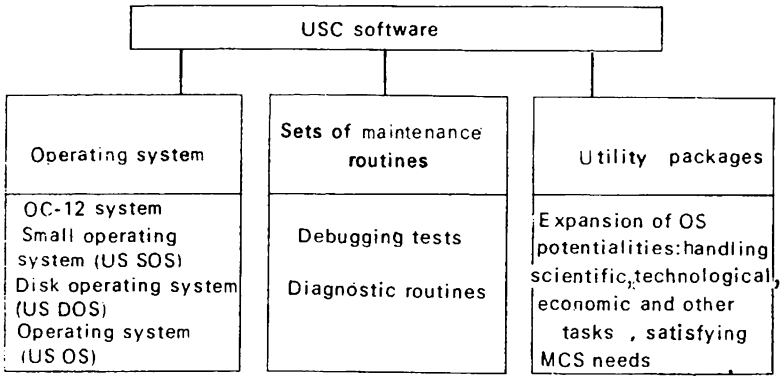
USC software
Operating system
Sets of maintenance routines
Utility packages
OC-12 system
Small operating system (US SOS)
Disk operating system (US DOS)
Operating system (US OS)
Debugging tests
Diagnostic routines
Expansion of OS potentialities: handling scientific, technological, economic and other tasks, satisfying MCS needs

Fig. 3.3. USC software

optimum use of system capabilities and various debugging and diagnostic means. There are disk operating system (US DOS) and operating system (US OS). The US DOS is mostly effective with junior models and is intended mainly for solving economic tasks; the US OS is universal.

The US disk operating system is very flexible and permits one to use the disks and tapes simultaneously, control input/output without excessively occupying the temporary storage and the processor with the control program. DOS can handle up to three tasks at a time. The US OS provides greater capabilities: it can solve up to 15 tasks simultaneously if the set of external devices is sufficient. It is fully independent of the types of devices and features dynamic storage allocation and the capability to handle priorities with many tasks. The OS and DOS are not compatible. The program prepared for DOS cannot be used with OS and vice versa. New disk operating system DOS-2.0 admits the teleprocessing of data.

The operating systems (Fig. 3.4) comprise control and processing programs. Let us consider some elements of the operating system. The control programs monitor functioning of the processing programs and furnish them with the required data. Three groups of programs are distinguished.

Job control. This program ensures processing of a continuous flow of jobs: reading, sequencing, input/output allocation, transfer of control to supervisor.

Data management. This program plans and controls the exchange between the main storage and peripheral units, provides the user with convenient methods of access to the data irrespective of the type of the unit which holds them.

Task management. The program is based on a supervisor. It handes the interrupts, satisfies the requests for the main storage, transfers

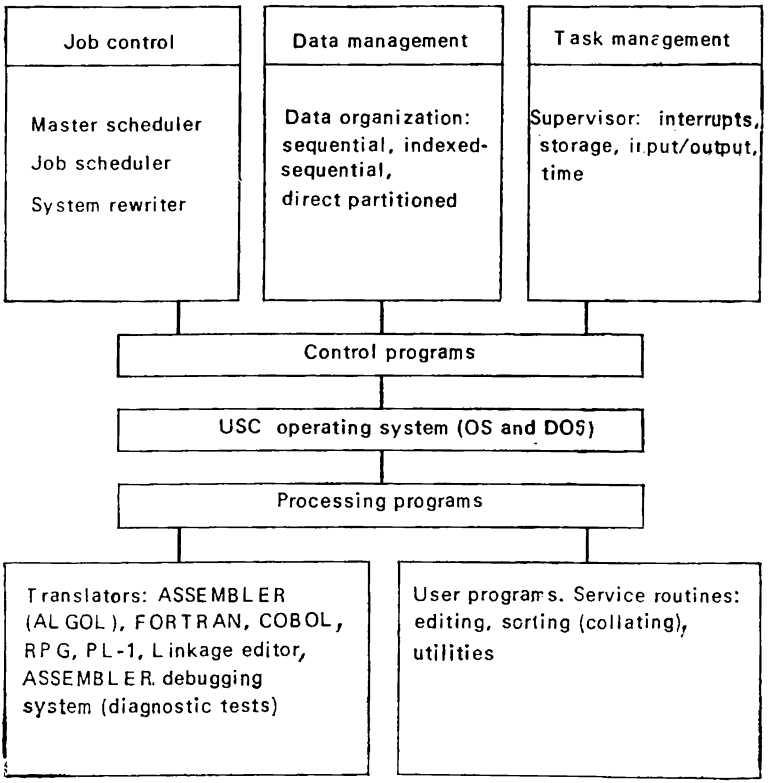
Job control
Master scheduler
Job scheduler
System rewriter
Data management
Data organization: sequential, indexed-sequential, direct partitioned
Task management
Supervisor: interrupts, storage, input/output, time
Control programs
USC operating system (OS and DOS)
Processing programs
Translators: ASSEMBLER (ALGOL), FORTRAN, COBOL, RPG, PL-1, Linkage editor, ASSEMBLER. debugging system (diagnostic tests)
User programs. Service routines: editing, sorting (collating), utilities

Fig. 3.4. USC operating system

task module management, completes the tasks, ensures clocking, etc.

Now consider some groups of the *processing programs.* These include service routines intended to perform editing, linkage and other functions frequently encountered in data processing. The service routines comprise linkage editor, sorting (collating) routines and a set of auxiliary routines (utilities). The linkage editor links the routine modules or segments. The sorting (collating) routine sorts or collates (in the increasing or decreasing order) the data comprising a fixed- or variable-length records. The utilities perform transfers from one external device to another, edit, reorganize and modify

programs and data in system libraries, change the data structure in files, list data or programs. Note that the sorting (collating) routines are often used in PP MCS.

Languages and translators. An algorithm and a program should be prepared for each task to be solved by the computer complex. The algorithm generally implies a simplified procedure for solving a complex problem. The program is also an algorithm but translated to the machine language. The third-generation computers feature a language system forming three hierarchic levels (orders).

The higher-order languages include the so-called *problem-oriented languages*, i.e. those best suited for solving tasks of a particular class. The FORTRAN language was developed for engineering tasks, COBOL for economic tasks, ALGOL for expressing new algorithms (not included in the software of junior USC machines). The RPG language is used for printing documents at the output of the computer. There is also universal language PL-1.

The next level is occupied by the computer-oriented languages, i.e. those best suited for a computer of the given type and each intelligible only to a specific machine. These languages include ASSEMBLER. The list of computer commands forms the computer *code language* which is the lower-order one.

It is relatively easy to develop and debug the program in the higher-order language since it is very close to the natural language used by the engineer to formalize the solution of his task. The program written with the symbols of this language is transferred to the medium (punched card) and loaded into the computer. The program is translated into the machine language by the computer itself. A special program, called translator, is used for this purpose. This is rather a complex program. Therefore, the set of translators in the computer is usually limited. The translators are included in operating systems OS and DOS.

The translated program is somewhat worse than the program prepared by an experienced programmer in ASSEMBLER. It requires more storage capacity and has a lower speed.

During the machine operation, the program, source data, intermediate and final results should be stored in the temporary (internal) storage. If the storage capacity is not enough, the program is broken down into parts (blocks, segments). In this case the start of the program and the data sufficient to initiate the program are stored in the temporary storage. The remaining data are held in the external storage. After the first part of the program is executed, the temporary storage exchanges information with the external memory. The second part of the program and the required source data are retrieved from the external memory. During the exchange the processor can solve another task, while the exchange procedure will be performed by a channel processor. The division of the program into segments should

ensure the optimal route of exchange between the temporary and external storage devices.

Set of applied programs. The program compatibility of the computer system provides developing and accumulating applied program packages (AP) for different classes of tasks of optimal operation of electric power plants. In the power industry AP is often called specialized application software (SAS).

3.3. Modular Computers

The other family of the third-generation computers is the modular (building-block) computer system (BBCS) intended for process control of units and factories.

Organization of system. The structure of this system is similar to that of USC and also consists of autonomous modules. Now consider particulars of separate types of functional devices: central control and data processing devices (universal and special processors), storage (internal end external storage devices), I/O devices, intrasystem communication (channels), terminal devices.

The BBCS system comprises processors with a speed of up to 100-200 thou.operations/s admitting extension. Up to eight I/O devices can be connected directly to the processor. The system utilizes storage of three types: a modular temporary storage for 4096 16-bit words, a permanent (read-only) storage including a microprogram unit for controlling the computer and external storage devices on tapes, disks and drums.

The *system extension* is realized by installing a special (arithmetic) processor performing multiplication and division, and by connecting up to 16 additional I/O devices using an input extension.

The BBCS uses three types of channels for providing communication between the computer components. The most rapid channel is used for data exchange between the processors, temporary and permanent storage devices. The second channel of the junior machines has the same purpose and application as the selector and multiplexor channels in USC. The third channel sets links with remote devices.

Peripheral units. In addition to the traditional external devices considered above (storage devices on tapes, disks, punched cards. plotters, displays, etc.) BBCS utilizes special means for connecting the computer to the operating personnel (operator) and to the controlled object. Provision is made for reserving some of these connections. The system is compatible with the typical telemetry and data transmission equipment which is very important for the electric power plant and system MCSs. To connect the computer system with the controlled process, use is made of switching units which connect the required actuating modules and sensors of the

controlled process to the computer. Also employed are the units for converting the analog signals of the sensors to the digital code and special units for converting discrete position signals (e.g. ON-OFF) into the machine code. The numerical signals in which the value of the controlled magnitude is represented by the number of pulses (the number of operations, speed of rotation, etc.) are converted similarly.

To supply the executive commands to the controls, special command output modules are provided for converting the digital signal to the control action of the on/off, increase/decrease type. The output command may be pre-converted into the analog form. To keep technical documents and present data to the operator, there are various methods for printing out the information or displaying it at special operator consoles, depending on the specific features of the controlled process.

The *delivery set of the machine* may be varied. It should be borne in mind that the BBCS-series modules comprise four characteristic groups.

1. The main modules include: processors, a temporary storage with a capacity of 4K 18-bit words, a storage extension, arithmetic extension, I/O extension, direct-access channel, interprocessor communication channel, external storage on disks, timer.
2. The I/O modules include: punched tape I/O devices, process data printer, keyboard printer, data display stations (DDS), graphic display stations (GDS).
3. Modules for controlled process connection include: analog-to-digital converters, switches, switch control devices, switch control extension, signal amplifier, filters, normalizers, modules for discrete data input group control, input of initiating signals, input of code control numerical signals, and position control signals, switching, group control of discrete data output, extension of discrete data output.
4. Synchronizers include: a channel adapter interface extension, and a duplex register.

3.4. Time-Sharing Computer Centers and Computer Networks

The present-day MCSs have a number of grave disadvantages. High costs of the computers involve heavy outlays, while their relatively low reliability necessitates installation of additional stand-by machines, which in turn, increases the MCS costs. At the initial stage of MCS development it is impossible to fully load the computer center because of lagging behind of special software. This also decreases the effectiveness of MCS.

Time-sharing computer centers. The up-to-date state of computerization provides for using MCS with time-sharing computer centers (TSCC). These centers serve several MCSs simultaneously. TSCC are mostly efficient in large cities where four or five big computers ensure a reliable servicing of about ten management and/or control systems at relatively low costs of communication between the users and TSCC.

Integrated information system. The development of the TSCC systems and their further integration by information networks make

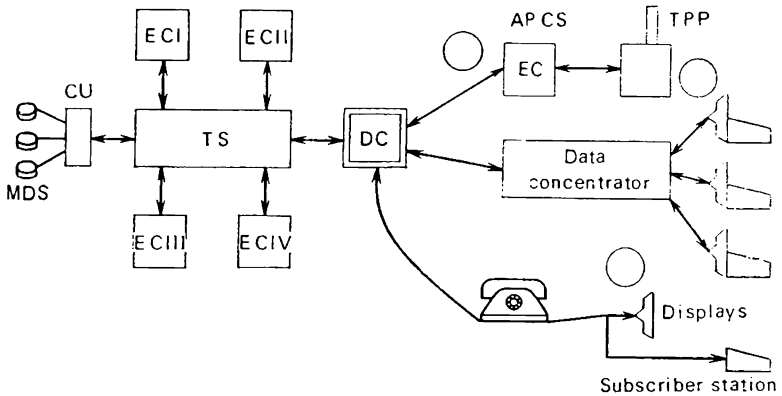

Fig. 3.5. Simplified diagram of computer network

it possible to pose the problem of organizing an integrated information system or computer network. It is planned to create a special branch of the national economy for centralized supply of information to all the users. Such a system will probably resemble the power grid of the country which carries out centralized supplies of electric power and heat energy. Integrated information system ENERGIYA might be the forerunner of such a system.

Figure 3.5 represents a simplified diagram of an area of the future computer network. A group of big computers EC I—EC IV operates on a common field of the temporary storage. Connected to the field is a dispatch computer (DC) which controls the flows of jobs and organizes the interaction of main computers for solving the tasks in the time-sharing mode. DC connects the users through special communication channels (allocated or leased). Fig. 3.5 shows the users of three types. These are thermal power plant atomatic process control system (APCS) including its own computer which is connected to the computer network to solve particularly complex or urgent real-time tasks. The required software may be held in the memory of the time-sharing computer center (TSCC) or may be stored in the thermal power plant computer center, and loaded in the TSCC memory together with the source data.

Another type of the user shown in Fig. 3.5 is a design organization

engaged in the development of the power system. The working stations of designers double as the subscriber stations. They are linked by data concentrators and communication channels to the dispatch computer (DC).

The third type of the user is an individual user (subscriber station). It gets in contact with TSCC via a telephone and converses with the machine using a domestic TV set provided with a special alphanumerical keyboard. The user can obtain various information, such as arrival and departure of trains and transport vehicles, performances, telephone numbers, etc. The user can also improve his professional skills by using TSCC in computer-aided instruction mode (CAI).

The system provides programs and resources for solving the required problems. Its external storage can hold the data files necessary for the user (files of data on daily load of the power system and its areas, data on river run-off, etc.) for a long period of time.

System effectiveness. Such a system would drastically cut total costs of MCS by decreasing the required capacity of computers because the load peaks of separate users are not overlapped. The different time zones will also contribute. The effectiveness will be further improved by decreasing the required reserve capacity of computers since the integrated information system will need only a centralized (system) reserve rather than individual one. The system will provide for employing more powerful and advanced computers which considerably diminish capital and operating specific costs for unit information processing as compared with small and medium machines. Finally the creation of such a system will simplify the centralized maintenance (operation) of the information network thus offering good economy by reducing the attending personnel.

The power system computer centers are designed as the time-sharing centers for all the factories or their equivalents of the USSR Ministry of Power Industry located within the territory of the power system.

3.5. Organization of MCS Hardware Complex

On-line control and planning. The Energiya BMCS is a total (integrated) management and control system intended to handle both the organizational and process control tasks. Because of this the complex comprises the on-line control section and the planning section. Such a division has affected the structure of the hardware complex (HC). MCS hardware complex includes two groups of devices performing different functions. First the devices intended to participate in the process control which is carried out in real time. In the power industry the process control takes the form of the dispatch control (service). Some components of the hardware complex which

participate in the dispatch control are called real-time information complex (RTIC), the other components of MCS hardware complex, the computer complex (CC) intended primarily to solve the planning tasks, optimization including.

The complexes may include different (more often program-compatible) computers. The computer complex solves the long-term, dispatch and economic tasks, RTIC, the information and routine process tasks. The information tasks include the receiving, collecting, processing, recording and displaying of the information arriving at the computer center. After verification, the status of the main equipment is indicated and the operation variables are compared with the preset parameters.

The on-line control tasks are more diverse. They include forecast of loads (from the automatically collected data), load and power flow distribution calculations, updating the operation schedules, etc.

Hardware complex components. Thus, the MCS hardware complex comprises the real-time information complex and the computer complex:

$$\text{MCS HC} = \text{RTIC} + \text{CC}$$

In its turn, RTIC for the higher levels of management (ACB, CCD, USSR PG) may include the information and computer subsystems.

Each component of the complex comprises three functional groups of devices:

—the devices for collection, communication and preparation of data;

—the computerized data processing devices;

—data displays for the operator (engineer-on-duty).

The computer complex may additionally include the fourth group of devices intended to prepare and formalize the machine documents—a document handling system. Direct digital control with the help of the real-time information complex (RTIC) calls for devices to supply the control signals from the RTIC to the controlled plants.

Structure of the RTIC hardware complex for power systems and pools. RTIC is a multicomputer system operating in the real-time mode. It automatically inputs and processes the telemetry and alphanumerical information, controls the means for visible representation of data (displays, annunciators, instruments and mnemonic symbols of the dispatch control board), performs computations for controlling operation modes, automatic frequency control, automatic regulation of power transfers, voltage, etc.

Requirements for the RTIC hardware complex. The above-listed functions of RTIC call for utmost reliability which is achieved by using stand-by facilities and automating the data input to the maximum possible degree. It is necessary to provide simple and conve-

nient means for the man-machine communication, e.g. a special conversational system for input of new and updating of available data, initiating and tracking of the on-line control tasks.

RTIC subsystems. The developed real-time information complex comprises two subsystems: a data control subsystem and a data processing subsystem. The first subsystem ensures automatic collecting and processing of telemetry information, control of display facilities, and automatic control. The subsystem utilizes small computers with peripheral units adapted for real-time operation.

The second subsystem carries out real-time calculations (planning and updating) of operation parameters using information supplied from the first subsystem. It solves the problem of real-time accounting and analysis of energy resources, condition of the main equipment, technical and economic indices, etc. The subsystem is based on medium (large) computers (EC-1022, EC-1033, EC-1040, etc.) and makes it possible to construct mass data files. The required masses of data are exchanged between the subsystems. Each subsystem is fairly autonomous and interchangeable.

3.6. Stages of Construction of RTIC

The basic functions of the RTIC hardware complex are as follows:

1. Ensuring operability of the two-computer system with duplicating main functions (check and debugging routines, automatic change-over of the main functions to the stand-by computer, generator routine, terminal change-over).
2. Allocating functions among the computers of the complex—queuing the tasks for the single-computer and double-computer processing; dumping secondary tasks when changing over from the double- to single-machine processing.
3. Controlling digital indicators and mnemonic symbols of the dispatch graphic panel with duplication; effecting manual computer-aided monitoring of the panel; generating summary variables and telemetry signals.
4. Controlling representation on the operator display of the information on impermissible deviation of process variables and disengagement of elements or switches.
5. Relaying current information through the computer (transmitting real-time information through the inter-computer communications between the control levels, centralized reception of telemetry information), using the computer as a centralized data sink.
6. Monitoring the input data with accounting for the semantic and statistical linkage of the operation variables.
7. Analyzing the situation of the power pool by the data of telemetry — shaping a generalized concept of the situation by measurement results.

8. Improving RTIC on the basis of operation experience—modernizing the tasks, complementing the utility packages for new telemetry and display facilities.

9. Developing new service programs to simplify the work of the user, e.g. programs for automating checkout, updating and replenishment of the data base.

Stages of the RTIC construction. The multicomputer complexes are constructed in stages because of a gradual increase of the hardware. The RTIC designers conventionally distinguish four stages of the complex development.

The first stage — the complex with a small stand-by computer. The complex comprises three computers: two small and one large

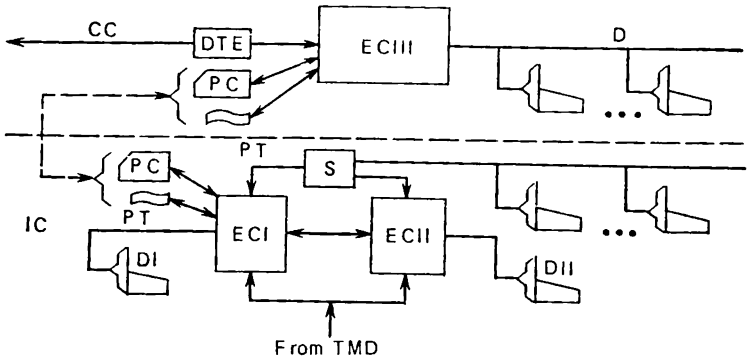

Fig. 3.6. Three-computer RTIC (TMD stands for TMDS)

computer. The data management subsystem (Fig. 3.6) comprises two small computers: ECI and ECII. Each computer has a temporary storage of 32-64 Kbytes, an external magnetic-disk and tape storage, punched-tape I/O, printers and real-time peripherals: digital and analog I/O modules, digital-to-analog and analog-to-digital transducers, interruption modules, etc. Each computer is connected with telemetry data sinks (TMDS) and displays (D). The telemetry analog devices are connected to the analog input modules and multichannel code-pulse PS devices to the digital input modules or through a special interface telemetry data sink (ITMDS) which reduces the required number of input and interruption modules.

Input of telemetry data into RTIC. The telemetry data input is initiated by both the computer (by polling TMDS) and TMDS (by the disconnect signals coming from TMDS). In case of TMDS with cyclic data transmission, the first variant is more advisable as it ensures simpler input algorithms. The second variant (TMDS initiative) suits better for TMDS with sporadic telemetry data transmission. Apart from the telemetry data, the computer receives signals

of malfunctions of the TMDS sets (mismatches, communication channel troubles, interrupts, etc.).

Connection of displays and TMDS. The displays are connected to the I/O modules and interrupt modules of the real-time peripherals of the computer. One of the displays is connected to each computer directly, while the rest through selector switch (S). The displays mounted at the dispatch center may be arbitrarily allocated among the two computers with the aid of the selector switch. Two displays directly connected to the computers are arranged in the computer room for use by the operating personnel of the real-time information complex.

Operation of small computers. Under normal conditions one of the computers (e.g. ECI) is the operating one which performs all the functions of the data management subsystem, while the second computer is an unloaded reserve. The real-time system is loaded into the operating computer and a group of displays is connected to the latter by selector switch (S).

The second computer is used for the debugging of programs and no telemetry data are loaded into it. If the operating computer fails, the debugging of the second machine stops and the real-time system is loaded into it from the magnetic tape. The displays are switched to ECII. The change-over from one computer to another takes several tens of minutes and results in the lost of all the information held in ECI.

Without the debugging of ECII, the time of the change-over to the standby computer will take only several minutes and the telemetry data files will be retained. To operate the complex in such a mode, the real-time system is loaded into both computers. Now both computers receive and process telemetry data. When changing over to the standby computer, only the operating computer information is lost.

At the first stage of development the data processing subsystem comprises one large computer with a conventional set of peripheral units. As a rule, the computer operates in one-program mode. The source data for calculations are supplied from the punched cards and tapes and the results are output to the alphanumeric printer (ANP) or a tape punch. This computer solves all the tasks (planning of operation modes management, process and statistical data analysis).

The second stage — integration of small computers in a two-computer complex. At this stage also two small computers of the real-time information complex (RTIC) and one large computer of the computer complex are employed. To improve reliability of operation and preclude loss of information the small computers are combined to form a two-computer complex. The inter-computer exchange and automatic change-over of displays from one machine to another are

organized. Under normal conditions both computers receive and process the telemetry data. The operator allocates the displays between the computers.

The information inserted by the operator from the display keyboard to one of the computers is transferred to another computer via the inter-computer communication. Substantially identical information is held in the temporary and external storages of both computers at any moment of time.

If one of the computers fails, the operable machine will change over to itself the displays of the defective computer. This increases the reliability of the system by full redundancy of all its functions and the capacity under normal conditions owing to the allocation of the data displays among the computers. Change-over to single-machine (simplex) or double-machine (duplex) mode, control of telemetry data input, allocation of the displays and other operations are executed from the display keyboard of any computer.

Various techniques are used for finding faults of the working or standby computer. The faults may be found by a long (over 15 s) occupation of the temporary storage working field or stoppage of cyclic problem solving. In this case a warning signal is applied to the operating personnel for the change-over of the displays.

The data processing subsystem comprises one large computer which is not linked with the small machines. It is equipped with the facilities for automatic data exchange with remote data-use points and a multidisplay conversational system. This is realized by the junction of the computer with the data transmission equipment (DTE) and a group of displays. Use can be made of the computer-to-DTE junction (interface), type "Accord-1200". The selection of a subscriber, i.e. the connection of DTE to the required communication channel, is carried out manually by the operator. This procedure can be automated with the aid of the automatic switch of the long distance communication channels.

The Soviet industry manufactures multidisplay systems types EC-7066 and "Ekran-M". The former comprises four alphanumeric displays with keyboards. The latter is intended for operating a computer with up to eight displays via the allocated or switchable telephone channels.

The third stage — the three-computer complex with interlevel exchange. This stage is characterized by creation of an integrated three-computer complex and organization of the intermachine exchange (IME): small computers — large computer. IME utilizes the channel-to-channel adapters (CCA) of the small and large computers for duplex exchange of control signals and data files. The construction of the channel-to-channel adapters differs drastically depending on the type of the interfaced computers.

The channel-to-channel adapter receives and executes commands,

transmits information in two ways, verifies data, generates information indicative of the device status (readiness for executing commands, completion of exchange, etc.). The three-computer complex uses two adapters which are linked both to the selector channel of the large computer and to the program channels of the respective small computers.

In addition to displays, small computers are connected to the multi-access data representation facilities — digital instruments and mnemonic symbols of the dispatch control panel, annunciators, etc.

The alphanumerical annunciators have not yet found wide application. The "Visinform" annunciators manufactured in Hungary have adapters for connection to the EC-1012 computers but they also can be linked with the machines of the modular computer system via a non-standard adapter. Manual management of the mnemonic symbols and manual input of information for the digital instruments are effected with the aid of the display keyboard.

As the complex is developed, the second large computer is installed. Under normal conditions one of the machines, i.e. the system computer, operates within the three-computer complex to perform routine calculations with the use of the data supplied from the small computers, display keyboards and data transmission equipment (DTE). The background region of this computer is used for debugging and other off-line work. The second machine, i.e. the standby computer, operates off-line. If the system computer fails, the operating personnel manually connect the displays of the small computer adapters to the standby computer. The operator replaces the magnetic disk packs from the defective machine to the standby one and loads the software to the latter.

The fourth stage — the integrated four-computer complex. The complex comprises four interconnected computers: two large and two small computers. It is organized by symmetrical intermachine communications and a system for automatic (semi-automatic) changeover of the displays from one large computer to the other (Fig. 3.7). Two such devices are connected to the channel of each computer. The large computers are linked by the channel-to-channel adapter coupled to the selector (or multiplexor) channels of each machine.

A common field on magnetic disks of large computers is organized for the four-computer complex (Fig. 3.8). Two outputs to the magnetic-disk storage control units (MDSCU) provide for connecting the selector channel of any machine to each of them. Any computer can address any magnetic disk for data recording or reading. The tape storage control unit has similar capabilities.

Two inter-level exchange systems are created at the fourth stage: small (lower-level) computer inter-level exchange (ILE-L) and large (upper-level) computer inter-level exchange (ILE-U) systems. Now

the information is loaded directly to the machines which process it. The transit transfers are minimized and the control and processing subsystems become autonomous. The inter-level exchange is implemented with the use of standard teleprocessing hardware—multiplexors and modems.

The ILE-U system organizes the exchange of the production-statistical and process information of massive amounts with a twenty-four hour or longer cycle. These are primarily the data for the PEA section — consumption and reserves of fuel, electric power

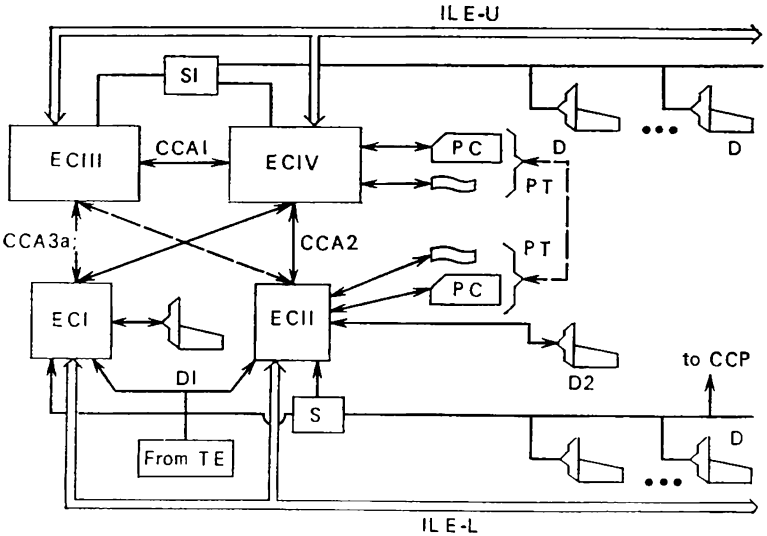

Fig. 3.7. Integrated four-computer RTIC

CCA1-CCA2—channel-to-channel adapters; *TE*—telemetry device; *D*—display; *S* and *SI*—display switches; *ILE-U*, *ILE-L*—inter-level exchange with upper and lower control levels

generation, specific consumptions, technical and economic indices of electric power plant operation, source and resulting data on plant operation calculations performed by the large computers.

System ILE-L organizes the exchange of data used in small computers. The exchange is carried out in small amounts with a cycle up to twenty four hours. This exchange includes hourly data of the daily register, information on changes in the equipment status, etc. The data fed from telemetry devices to the small computer are processed with the use of data compression methods and transmitted via ILE-L to the computer data sink. The small computer transmits only useful information to the sink. Only drastically changing variables are relayed (several tens of telesignals characterizing the status of separate switches of the transit power transmission line

may be replaced with a single summarized transit status signal). If necessary, the data sink may address the transmitting machine for more detailed information, e.g. cyclic transfer of the chosen variables or data on the status of separate switches on one of the power-generating units. To connect the communication channels to large computers, use is made of multiplexors, type МПД-1—МПД-3, conjugated with the multiplexor channel of the machine. The multiplexors can be connected to the channels of two computers for alternate use. The multiplexors ensure data exchange

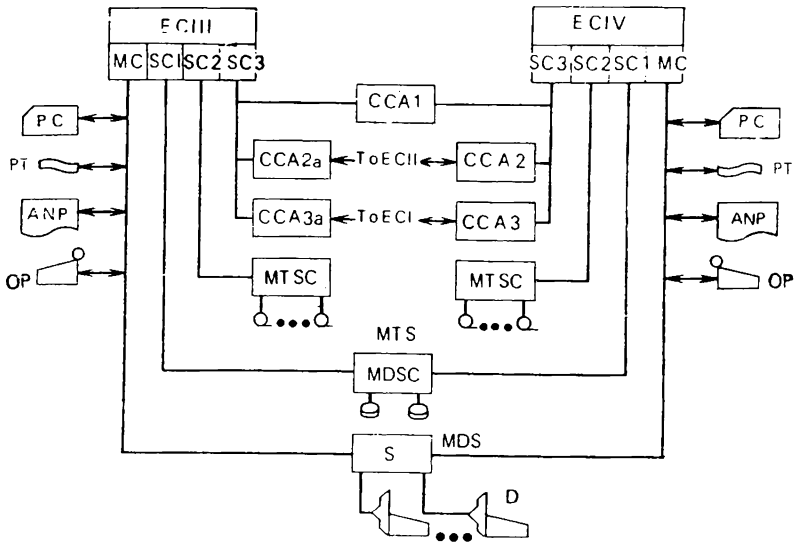

Fig. 3.8. Organization of common field of external memory and integration of computers into RTIC

between the computers of different control level, as well as between the computers and the remote data-use points via the telephone (telegraph) lines.

Small computer inter-level exchange. This mainly implies the transmission of data from the lower-level computer to the upper-level one. The small computer structure allows one to organize inter-level exchange (ILE) both by means of multiplexors and by connecting modems to the controlled installation connecting unit of the computer. The communication channels are connected either in parallel to the modems of both machines of the complex to provide data input/output facilities for both small computers, or via a selector switch to the working computer.

Organization of four-computer complex operation. Provision is made for normal and emergency modes of operation of the complex. Normally, all the four computers are in use. One of the large computers — ECIII — is a host computer, while the other one — ECII is a slave computer. To the primary computer are connected the displays and ILE devices. The exchange is intensified via the connections between small computers ECI and ECII, small computer ECI and host computer ECIII, host computer ECIII and slave computer ECIV. The data from the telemetry devices is fed to both small computers. The ILE-L information is supplied to the working computer ECI. The data inserted manually from displays and arriving via ILE-L at ECI are transmitted via connection I-II to computer ECII. The data from the small computer are relayed to the host computer on the initiative of a small computer, and through connection III-IV to the slave machine. Any of three computers can be accessed from any display.

When organizing a common memory field of ECIII and ECIV on magnetic disks, the information received via ILE-U may be recorded on the common field disks rather than transmitted via connection III-IV.

The display switches allow arbitrary allocation of the displays between ECIII and ECIV. In this case the conversation with both computers is possible even if the intercomputer communication III-IV is disrupted. In emergency operation, when ECI fails, the displays, panel and annunciators, and ILE-L are automatically changed over to ECII. Connections I-II and III-I are automatically blocked, while connection II-III intensifies. If host computer ECIII is damaged, displays and ILE-U are changed over to slave computer ECIV; connections III-IV and I-III are blocked and connection I-IV is intensified. The computer modes are selected by the display operator of the respective machines. It is advisable to establish a single console for selecting and monitoring the operation mode of the entire complex.

Computer complex (CC). The computing functions are executed by all-purpose computers incorporated in the complex. The CC problems can be solved either on an autonomous machine or in the background regions of the computer. A separate computer complex becomes advisable only if the resources of the real-time information complex (RTIC) computers reserved for the computer complex problems prove insufficient. Separate CC is based on an all-purpose computer, types EC-1035, -1040, -1050, -1060 with a large-capacity temporary memory (512 Kbytes and more), a large-capacity magnetic tape and disk storage, a double set of I/O devices. The CC machine ensures off-line redundancy of problems handled by the all-purpose computers of RTIC. To achieve this the computers included in the information complex and in the computer complex should be program-compatible.

The evolution of computer complexes should proceed along the path of creating the computer networks (time-sharing computer systems) (CN) based on a multi-display system and a group of remote data-use points (subscriber stations).

3.7. Frequency and Active Power Control Hardware

Frequency and power control is one of the most vital functions of the automatic dispatch control system (ADCS). Sometimes, this function is performed by an autonomous specially established computer complex, while on other occasions the solution is reserved for RTIC. The analog devices and small computers make the hardware for the purpose. There are four possible variants of automatic frequency and power control center (AFPCC): an analog complex, one small computer duplicated by an analog complex; two small computers with mutual duplication; utilization of multicomputer RTIC. The first three variants are essentially the successive steps in the development of automatic frequency and power numeric computer system created in power pools and systems. The fourth variant seems most promising.

Now consider the structure of AFPCC complex comprising two small computers. It is similar to a two-machine real-time information complex. To both computers are connected telemetry devices for loading data required for AFPCC (total power, regulation range and rotation reserve of power plants, values of transfers via transmission lines, teleinterlocking signals, etc.). The devices for transmitting control signals (remote control) are additionally connected to the computer output. TMDs included in RTIC for polling information can be used for the input of the telemetry data. However, a fully autonomous system for collecting and transmitting data for AFPCC is more reliable.

In addition to TMDs, the displays are connected to the computer and the inter-machine exchange is organized. The data displays include two displays permanently connected to each computer, a display arranged directly in the machine room and an AFPCC display and console connected to both computers through an automatic selector switch. The dispatcher's display has a special keyboard. The AFPCC console accommodates a group of annunciators to indicate the mode of AFPCC and TMD status, as well as several toggle switches for emergency change-over of the system operation mode.

Organization of system operation. When one of the computers is working, the other stands by. Both computers simultaneously receive and process telemetry data, generate control signals, exchange status signals and information manually inserted from the display consoles. The working computer additionally controls the dispatcher's display and the AFPCC console and supplies control signals to TMDs. If the

working computer fails, the standby one automatically changes over the display and AFPCC console to itself and intensifies the control signal output circuits. If the standby computer fails, the working computer selects the emergency one-machine mode and gives a warning signal to the operating personnel.

Under normal conditions the values of the control signals are exchanged in a preset cycle between the machines and are compared. Should any control signal deviate beyond the permissible limits, the working computer supplies the appropriate signal to the AFPCC console annunciators. Simultaneously the standby computer receives a signal which precludes intensification of the control signal output during change-over of the standby computer to the working mode. The output is deblocked by the personnel manually after the cause of the deviation is analyzed and eliminated.

3.8. Software Features

General requirements for software. Software is a combination of programs for achieving the objectives and tasks of MCS. The software quality is vital for proper functioning of the MCS hardware. The quality of software is characterized by the correctness of the results, computing time t less than the permissible time $t < t_{perm}$ but not mandatory minimum, the program length (storage capacity), convenience in use (simplicity of instructions, easy job for the operator, high resistance to malfunctions and interrupts, possibility of editing the computation run, replacement of disks or tapes, etc.), simplicity of subsequent modifications, convenient debugging, degree of unification (the possibility of using the software of the task or its segment for handling similar tasks of the same or cognate controlled plant).

The software quality is affected by the statement of a task, languages and translators used, library available, methodological documents, qualification and scrupulousness of the programmer, etc.

Now consider the specialized applications software (SAS) intended for solving the tasks of management of power system operation. The contents of SAS is determined by the set of tasks. For clarity, let us refer to the software for real-time information complex (RTIC SAS). RTIC SAS is based on the real-time system. The system ensures automatic receipt, processing and representation of the current data. This is a complex of time-sharing programs. The complex may be divided into two groups: standard programs and utility programs. The standard programs include the disk operating system which controls operation of the complex as a whole and input/output (e.g. telemetry data input, display control, etc.). These standard programs are called drivers. The bulk of the program is held on magnetic disks. The required program is called to the temporary

storage only for the time required for its run. The disk is addressed either by the utility program per se or by the operating system through the disk program resident held in the temporary storage. A special area (working field) is assigned in the temporary storage of the called programs where only one disk program can reside at each moment of time. The operating system supervises the utilization of this area.

The drivers held in the temporary memory ensure data exchange between the external devices (TMDs, displays) and the allocated areas of the temporary storage, called buffers. The information is retrieved from the buffer by the utility programs. To receive telemetry information one buffer is allocated which is adapted to hold the entire amounts of data fed during one cycle. Several buffers are reserved to exchange data with the displays. To save the machine memory, the number of the buffers is less than the number of the displays, for instance three buffers are used alternately with sixteen displays.

Utility programs. These programs are divided into the cyclic and sporadic programs. The former process the telemetry data and are started by the timer. These programs reside in the temporary storage and ensure modification of telemetry data addresses, determination of the type of the information received (telemetry data TD or telemetry signals TS), verification of TD and TSs, current averaging of TD, monitoring of TD ranges, monitoring of changed TSs, checking of telemetry device condition, generation in the computer temporary storage of mass data of instantaneous and averaged values of TD, current status of TSs, changed TD, telemetry device failures, etc. These programs originate on the magnetic disks, the files of telemetry variables which fall beyond the preset limits and TSs which changed their status.

The other programs are sporadic and serve the tasks of representing the information on displays (and on other output devices). The conversational system is the main element of the sporadic programs. It ensures, jointly with the display control program, the generation, transfer to the computer and decoding therein of the directives, set on the display keyboard, start of the appropriate utility programs, editing and output of the information on the display screens. The conversational system calls the respective programs from the disk to the temporary storage for displaying various types of information.

The sporadic programs include those for TD scaling prior to displaying on the screens, processing daily record data inserted manually, documentors, a number of service programs for input and editing of the system software.

Data display on screen. The information displayed on the screen comprises a static part prepared beforehand (table pattern, electric circuit diagram, etc.) and a dynamic part which is fed from the

respective telemetry data files of the temporary storage and is renewed on the preset loop (numeric values of variables, two-position symbols of switching gear status). For some problems the dynamic part of the information is input manually from the display keyboard.

The display information tasks usually include representation of the block diagrams (e.g. segments of the network with updated operation variables); representation of the detailed diagrams of the power plants with updated operation variables and present status of the switching gear; output of the updated operation variable tables; output of the arbitrarily grouped indices in the tracking mode; storage and subsequent reviewing in the tracking mode of any telemetry data (retrospective analysis); automatic output of summarized signals on network switchings, impermissible deviations of the operation variables, telemetry device failure; emergency listing; manual input (from the display keyboard), processing and output of the daily dispatch schedule. The problems also include representation of the instructive-and-reference data (directions on the operating conditions, switching forms, etc.).

The complex of the service programs provide for replenishing and updating the software (scale factors and process variable ranges, bank of technological names of plants and loads, static parts of tables, diagrams, etc.) with the aid of the display screen without system interrupts.

4

MANAGEMENT AND CONTROL OF POWER SYSTEMS, PLANTS AND NETWORKS

4.1. Organization of PS MCS

The power system management control system (PS MCS) is a multilevel organizational and process control complex. It includes MCSs of power plants, electric network facilities (ENF), heat net) work facilities (HNF), automated process control system (APCS- of large power-generating units, APCS of substations. PS MCS handles the tasks of the process control and management information

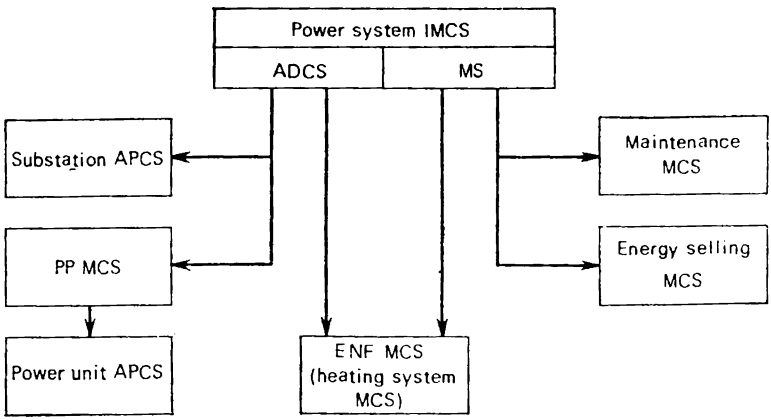

Fig. 4.1. Structure of integrated MCS of power system

and is a part of the integrated management control system (IMCS). The simplified structure of PS MCS is shown in Fig. 4.1. PS MCS comprises two main parts: automated dispatch control system (ADCS) and management system (MS). MS comprises MCS subsystems for maintenance of the power equipment and for energy selling.

Hardware. Consider preliminarily the PS MCS hardware (Fig. 4.2). It comprises the real-time information complex RTIC and the computer complex (CC). The information from the controlled installation sensors is fed via the telemetry equipment to the group of small computers ECI and ECII comprising RTIC.

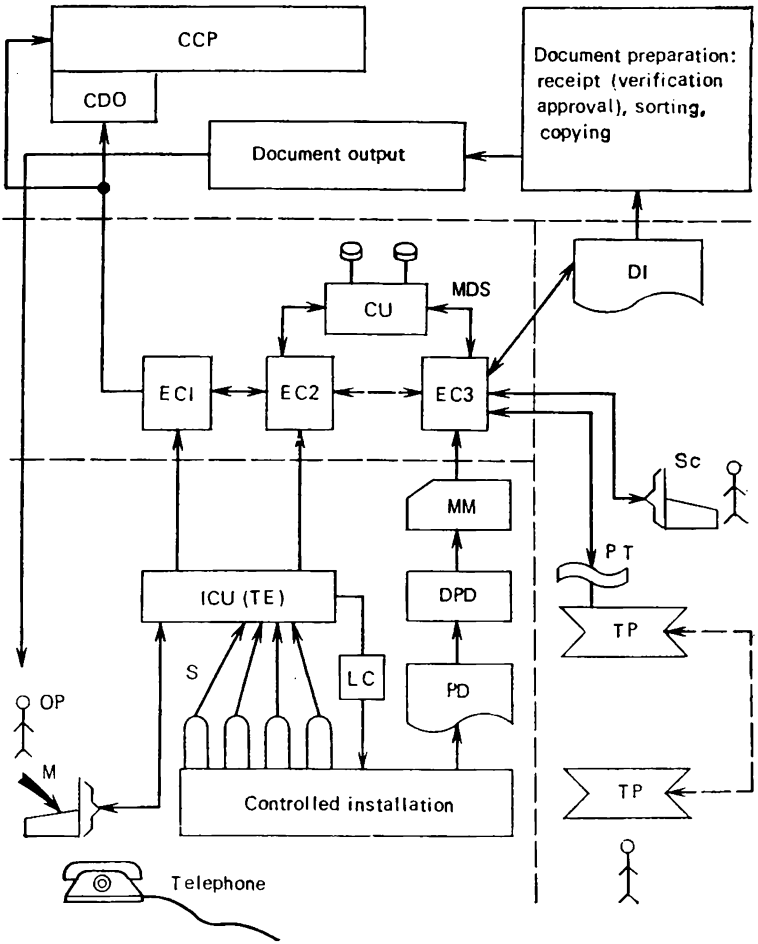

Fig. 4.2. PS MCS hardware

S—sensors; *OP*—operating personnel; *Sc*—screen; *TP*—teleprinter; *DPD*—data preparation device (punch); *ICU*—installation coupling; *M*—manual input of data received over telephone; *LC*—local control

A part of the information received over the telephone is set manually from the operator display. After processing the information is represented on the operator displays and on the central control panel (CCP) in the central dispatch office (CDO). Another part of information gathered manually or obtained from the primary documents is fed to the CC computer ECIII through the data preparation device which transfers the information from the primary document (raw data) to the machine medium (punched cards, punched tape,

magnetic tape). The data from the remote installations are transmitted to the same computers via teleprinters (TP). The information output by ECIII is received (verified and approved), sorted depending on the application, copied and handed over to the power system personnel (secondary documents). Simultaneously, the machine file is built with the aid of ECIII.

Primary and intermediate data acquisition and processing points. The development of the PS management and control systems is characterized by the ever-increasing number of the organizational and economic management problems to be handled and by the trend of computerizing all the entities of the system. This involves an increase in the amounts of alphanumerical information to be transmitted and processed, which gains an utmost importance in view of the centralization of the functions being carried out in the branch and the creation of the energy pools (EP) on the basis of the regional power departments (RPD).

To decrease the amounts of data to be processed in CC of power systems and organize the information flows, the hierarchic structures for collecting and processing organizational and economic information are created in the power systems. A vast amount of information is initially processed in situ, at the power installations, where the peripheral data acquisition, processing and transmission points are established.

The peripheral points of two types are organized in the power systems: primary points and intermediate points (branches of power system CC). The primary points collect and initially process the documents, verify and update information, transfer the data to the machine media, transmit information to the intermediate point or directly to CC of the power system. On some occasions, the source data are partially processed on key machines or manually. The intermediate points receive information from the primary points and relay it to CC of the power system, process in situ a part of information with supplying the summarized data to the department computer center (DCC) and the required computation results to the primary points.

The peripheral data acquisition and processing points are usually organized on a three-level basis: power system CC — intermediate point — primary point, or on a two-level basis: power system CC — primary point, or power system CC — intermediate point. The structure of the data acquisition and processing system is determined in view of the administrative division of the territory served by the power system, remoteness of the power installations from DCC of the system, the size of enterprises and number of power units included in the power system, availability of the communication channels. If the power system serves several administrative regions the intermediate points are established in all the regional centers. The inter-

mediate points are also organized in towns having several power facilities or production enterprises.

The primary points are equipped with keyboard computers (KC) with punch attachments. The intermediate points may have small or medium computers. When organizing MCS of a power installation, it is advisable to combine hardware of the installation and of the peripheral point for executing MCS functions.

PS MCS subsystems. PS MCS includes a wide range of subsystems. The number, names and tasks of the subsystems differ radically, depending on the power system particulars. We present herein below a sufficiently wide set of MCS subsystems of this class which makes it possible for the designer to choose whichever he regards as primary for his particular goals.

1. Automated dispatch control system (ADCS).
2. Electric power and heat selling subsystem.
3. Power equipment maintenance subsystem.
4. Production control subsystem.
5. Technical-and-economic planning subsystem.
6. Perspective development (long-term planning) subsystem.
7. Logistics management subsystem.
8. Fuel supply subsystem.
9. Transport and haulage management subsystem.
10. Labour and personnel subsystem.
11. Accounting subsystem.
12. Finance subsystem.
13. Quality control subsystem.

Though the power system is a customer for capital construction, PS MCS usually does not include a construction management subsystem linked with the power construction MCS. This impedes collection of information and supervision of the capital construction on the part of the power systems. Some PS become creating such subsystems.

ADCS tasks. The real-time dispatch control is a part of the process control. The tasks of ADCS are diverse and encompass four time levels: long-term (routine) planning, short-term planning, on-line control, automatic control.

The long-term planning—month, quarter, year—comprises the problems of optimal long-term operation of hydro plants, elaboration of optimal plans for major and medium repairs, development and updating of power and heat generation schedules. The power system perspective development optimization problems are also related here. The planning problems include a lot of computation jobs: calculation of PS parallel operation stability, short-circuit currents, relay protection and automatics adjustment parameters, compilation of instructions for operation of the equipment, etc.

The short-term planning covers preparation of the operation sched-

ule for the next day (week). The load curves are computed for PSs, PPs and units, the current requests for outage and repair of the primary equipment, control gear and automatics are analyzed, the normal and emergency operation conditions are calculated.

The on-line control problems should be solved immediately. They should ensure the accomplishment of the planned operation conditions and, if required, optimal correction of them, elimination of emergencies and re-establishment of the normal power supply network under the post-emergency conditions, organization of the troubleshooting, and repair work.

The automatic control includes the problems of controlling normal voltage and frequency with the aid of a computer and accomplishment of the fail-soft functions.

Now turn our attention to the software of PS MCS.

4.2. MCS Information Software

The information software (IS) is a combination of the information elements: a system of information markers and qualifiers, machine languages, rules for organizing files and documents, etc. When constructing the information software, due regard is given to the contents and utility of the information, the structure, flow characteristics, methods of collection. An important principle of IS organization is the information unity which is the presentation of the information in a common machine language (ML).

The machine language is an artificial language for writing the information in a form suitable for input in the computer, storage and exchange. The structure of such a language is determined by the vocabulary and syntax which enables one to form a language unit, e.g. to formulate an inquiry for the information-reference system or a directive (command) for building a new file.

ML has several hierarchic levels: characters (alphabetical), words, statements (labels), documents. The first level is of no independent significance. The word is any meaningful set of characters without blanks (—). For instance: —EI — PRINTING — DAILY SCHEDULE — PAGING — CLEAR — AAAA —.

Statement, *label*, *attribute*, *document*. The statement consists of a set of words. A particular type of statement is label. The *label* is a minimum meaningful element of the process information. It includes a name (flag) and a value (estimate):

Label	
name	value

During data processing, the label value is subject to logic and arithmetic operations, while the label name is used to search the required information. The name may be simple, e.g. a designation of the installation, or

complex consisting of a base and a phantom, e.g. electric power production cost.

The MCS people often use the terms "document" and "attribute". The document is a legal medium of data used in MCS. It is a certain preset entity of mandatory parameters. An example of a document is an optimal daily schedule of power system transfers output by the computer and approved by a person in charge. They say the documents contain a certain set of attributes.

The *attribute* is the same as the label but its presence in the document is mandatory. Similarly to the label it comprises a name and a value.

When designing information flows for MCS, it is essential that the type and size (length or number of characters) of the label are chosen beforehand. To this end the attribute is described by a picture and can be either numerical (usually marked by "9"), alphabetical (letter "A") or alphanumerical (letter "X"). The picture specifies the type of the attribute and its length. The length is indicated by repeating the character. For instance, the picture of attribute "month" takes the following form:

month, pattern AAAAAAAA.

This means that eight letters are allocated for writing the month name. For the sake of briefness, this picture may be written as month, picture A(8) where (8) indicates the number of repetitions of the given character in the picture.

The lists of attributes and their pictures are established beforehand when designing the machine language on the principle of primacy of the secondary document.

Record, file, data base. A combination of attributes (labels) may be regarded as a certain record. A plurality of similar records subject to similar processing are merged into a data file. Each file has its own name and comprises two records: a description and a body. The description is a set of attributes characterizing the files on the whole: record name, type and number of records, type of devices which store the record, initial address of the file, etc. Since MCS includes a plurality of data files, the similar files are merged into complexes and an additional file holding the names (catalog) of all the files of the complex is organized.

A set of data residing in the computer memory is called the data base. The information contained in the data base is usually divided into four groups: normative and reference data — up to 45% of the entire capacity; planning data — up to 10%; on-line process data — 20%; accounting data — 25%. The normative and reference information is introduced once and is only updated as required. The planning and accounting data are most frequently generated inside MCS. The on-line process information is usually fed via the communica-

tion channels. To accelerate and simplify its processing, the message structure is unified to ensure a strictly definite arrangement of the attributes. The arriving information is preliminarily processed and allocated among the files.

Data bank. The backbone of the MCS information software is a data bank (DB). The data bank is a centralized set of data files in the same language which serve all the MCS problems that can be solved in the conversational mode. The data bank centralizes the information collected independently from different sources, allows a multiple use of the information after a single input, decreases the access time, provides for reorganizing the files without modifying the utility programs, permits the use of data from different files in various combinations, etc. The data bank comprises a data base and a base control program, i.e. the program for the input and allocation of data among files, updating and fetching of the required data.

Command language. A version of ML is a command language also called a macroinstruction language. Such a language consists of a limited set of quite definite commands (macrooperators) that can be executed by MCS. These commands, the set of which depends on the particular goals of management, may be diverse and very complex. They are most frequently used in the conversational systems and are embodied as functional keys of the display. By pushing, e.g., the DAILY SCHEDULE key, it is possible to print out the daily schedule up to a given (present) hour.

Data coding. The computers handle coded information. Therefore, all the physical values should be substituted by codes. There are two methods of coding: manual and machine. The primary document designer himself encodes the physical names, e.g. enters the code into the primary document. In so doing he refers to a special document, called classifier and listing all the codes in use. The codes are transferred to the machine medium (punched card) and are introduced into the computer. After processing the data, the machine outputs them jointly with the code. The user mentally substitutes the codes with the existing physical values or writes them in the document.

When such a method is used, the coding-decoding functions are executed by the operator and no machine time is spent. It is assumed that each operator serves a limited number of items and knows most of the codes by heart, so that the coding-decoding process does not take much time. However, if the operator is at a sufficiently high level of management, the number of the required codes may be very great, so that this method proves inadequate (especially under the on-line control conditions).

Machine coding. There is another method. Each physical value is input in the computer in a natural language. The code dictionary is stored in the computer memory. If the value being inserted was encoded previously, the computer assigns the existing code to the

new value. After processing the computer decodes the information and formalizes documents in the natural language. If a given item was not previously encoded, the machine assigns a certain code and enters it into the system dictionary. Now the man fully frees himself of the coding-decoding operations. However, the machine spends a lot of time for searching the required code in the dictionary, especially in case it is on magnetic tape. The natural name (even abbreviated) is usually longer than its code, and this considerably increases the I/O time.

However, if the abbreviated names are used, the input data are grouped with similar items and the dictionary is held on the disk, this method may prove more efficient. Its advantages will grow as the capabilities of computers are increased. To increase the efficiency of the machine coding, it is necessary to elaborate rational methods of coding and utilization of the computer dictionary. For instance, all the information from, e.g., power plant may be divided into several classes and each class may be labelled with its particular code. The remaining part of the item name in the natural language should be added to the above-mentioned code. In this case the computer in coding will search not all the lists but only the list of a given class. This considerably accelerates coding-decoding.

Coding systems. The simplest coding system is a serial system. Each item (e.g. power system name) is substituted with a serial number. All the power systems of the country and all the power plants (e.g. of one power system) can be coded in such a way. More frequently used is a serial-parallel system in which the items to be coded are divided into groups and a definite set of numbers (with reserve) is assigned for each group. A decimal code is used for coding. Two high-order digits—9 and 10 are allocated for the branch number; digit 8 corresponds to the sub-branch. The sub-branch is divided into ten groups (digit 7), the group into 10 subgroups, the subgroup into 10 types, the type into 10 000 items. Up to 10 billion names can be coded by such decimal codes (without blanks between the sets of numbers).

Classifier. Coding-decoding operations are carried out with the aid of a special document (book, list, set of tables, etc.) containing the name of the item included in the range of products and its code. Such a document is called the classifier. A complex of interrelated classifiers makes a part of the MCS information software.

Data bank formation and functioning. The diagram of the data bank formation and functioning is shown in Fig. 4.3. The top level of the figure represents the external information software. The source information (primary documents) is translated to the machine media and prepared for the input to the computer. The data on machine media are batched into three characteristic groups: documents, standards, and classifiers. The real-time information is inserted not

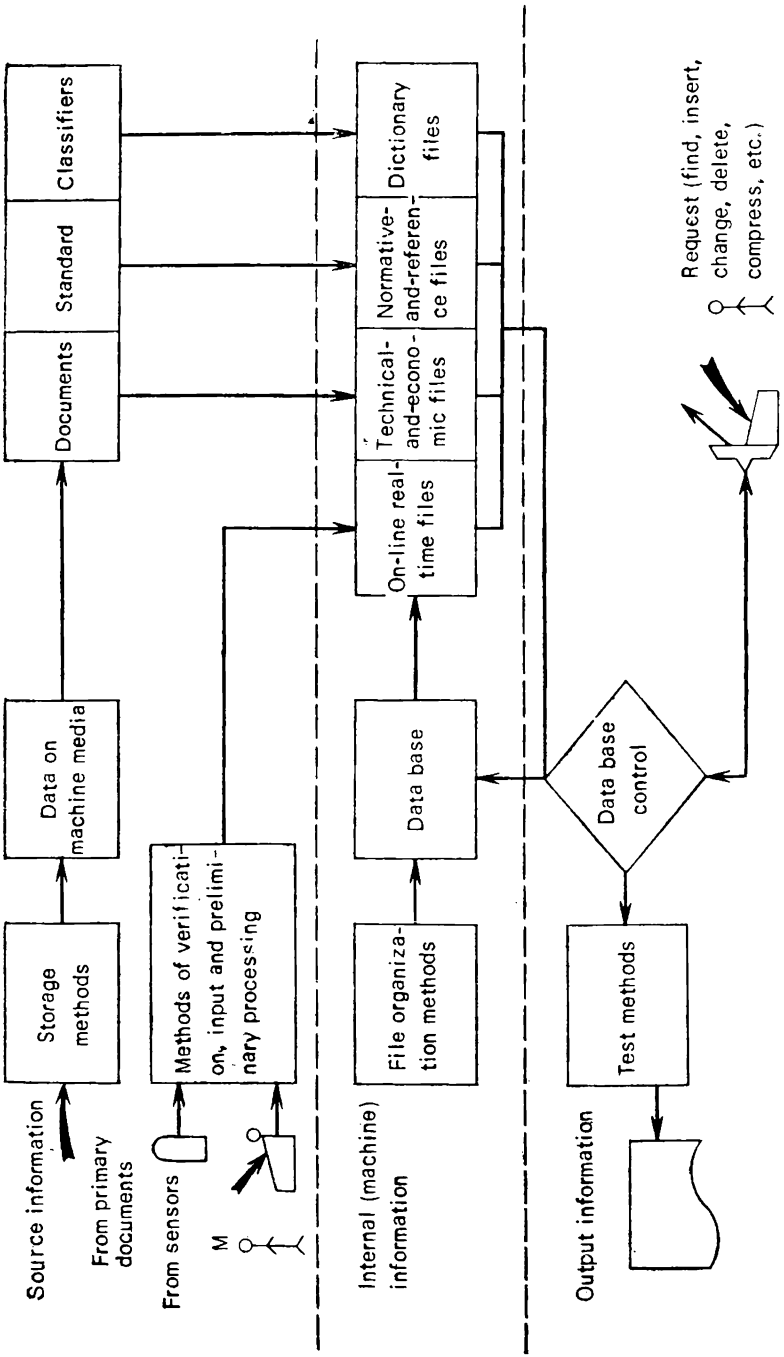

Fig. 4.3. Formation and functioning of data base

only from primary documents but also from the source data sensors.

The middle level of the figure is the internal (machine) information software. Here the methods of organizing and protecting data files are very important. Four types of source data correspond to four types of data files: on-line real-time, technical-and-economic, normative-and-reference, and dictionary files. A combination of the files makes up the data base.

The bottom level represents the output information. The output information is transferred to the display or to the printer as a secondary document on the request from the punched card (tape) or display keyboard. Here stringent supervision of the document issue gains importance. The base control devices allow performing such typical operations as find, insert, modify, delete, etc.

The data banks are just being implemented into power industry and no considerable experience of their use has been gained up to now. A high labour input involved in the data bank organization dictates that they are used only for a complex of interrelated problems. It is very important to learn how the typical data banks are used.

4.3. MCS Typical Data Banks

Consider several typical data banks which constitute the cornerstone of the software. Let us start with enterprise management and control system (EMCS) data bank known as an integrated data processing system (IDPS). IDPS-1 is intended to serve enterprises with a discrete nature of produce or for non-industrial applications, if the management information has a treelike structure. The system creates, modifies (updates) and processes the data base. The base comprises four files which hold the data on the items, their structure, manufacturing processes, working station. The files are interconnected by the address references. IDPS solves the problems of production tooling-up, on-line control, planning, etc. The bank requires 64 Kbytes of temporary memory. The number of disks or spools depends on the file size.

IDPS-2 differs in that it requires only 32 Kbytes of temporary memory, two disk and two tape storage devices; besides it has strengthened diagnostic means for generation of the system, which decreases the debugging time. IDPS-2 features two methods of main file organization: with a controlled sequence for constructing small files or the files with a low percentage of modification (less than 10% yearly), and files with separate indices (large files with a high percentage of modifications).

SINBAD-2 is a hierarchic structure data bank system. The system was developed by the Moscow Research and Design Institute

of Municipal MCS. The system can be used in any field of national economy. It proves most efficient in case of a constant increase in the types of the data handled, stringent requirements for reliability, the need for centralized control of the data bank with the aid of the teleprocessing means.

The system provides for creating and processing the data bank by means of problem programs which are independent of the method of storing data on physical devices. It is possible to add new types of data to the existing ones without changing the current problem programs, minimize the amount of information in the base establishing logic links between the segments of one or several data bases.

SINBAD-2 makes it possible to perform the following application program instructions: find, insert, change, delete. The base can be addressed by the application programs in COBOL, PL/1 or ASSEMBLER languages. The base is described only once, irrespective of the number of the application programs and languages used. The application program describes only a fragment of the data base to be processed. This protects the other data against inadvertent errors. All the modifications of the data base are entered in the operation record. This permits of restoring the base after occasional or intentional ruining.

SINBAD-2 comprises software for the declaration of the data base structure and direct access to them during operation of the bank. The bank requires 256 Kbytes of memory, three disk and one tape storage devices.

The BANK system. This system is intended for creating, updating and processing information of a centralized storage in which the data contents and interrelation are dictated by the user. The data base of the BANK system comprises one or several files and occupies one or several disk storage devices. The file is an independent part of the data array and the user can handle them as the entire base. The file structure (record contents, number of record types and links in between) is determined by the user.

The BANK system ensures stringent and coordinated control of the data base owing to centralization. The direct access to the data and address references from one record to another provide for a high speed of search and updating. The memory economy is afforded owing to the absence of the data redundancy. The data base is protected against random errors. The BANK system software comprises the data organization technique, data access aids, a language for the file structure declaration and a language for addressing the multi-purpose procedures. The system is based on standard complex EC-1022. If an additional disk storage is connected, the data base capacity can be increased.

There are also other data banks which are not covered by this book.

4.4. Collection, Transmission, Input and Initial Processing of Data in MCS

Instruments. The State System of Instruments (SSI) established in the USSR considerably facilitates the creation of PS MCS. SSI is a system of technical means for creating the production process monitoring and control systems. SSI standardizes the parameters of the equipment manufactured in this country. It is incorporated in the international (within the CMEA framework) system of hardware components for automatic monitoring, control and regulation. As regards their functions, SSI includes instruments for obtaining test data (sensors), test and control signal transmission devices (communication devices), devices for converting, processing, storing and generating commands (computers), devices for implementing the commands (actuators), and auxiliary power sources.

SSI is based on the modular principle which provides for creating a flexible structure and replacing individual units and modules. To achieve this modularity, the input and output signals, instrument scale calibration, specifications of the actuating mechanisms, overall and mounting dimensions of instruments are unified. Single requirements are introduced as regards the accuracy, reliability, operating conditions. The unification simplifies integration of the instruments into systems and complexes and connection of sensors to the computers.

Value and process monitoring at power plant. Let us distinguish between measurement (monitoring) of values and processes. The value is the only meaning of a variable. The process is a combination of the measured values in time. Measurements are performed by instruments and sensors. There are sensors with unified and non-unified signals. The sensors which put out DC of 0 to 50 mA or DC voltage of 0 to 5 mV relate to the unified signal sensors, all others to the non-unified signal ones. The non-unified signal sensors necessitate additional unification which causes complementary error.

The sensors used at the electric power plants can be divided into two large groups: continuous-signal sensors and discrete-signal (or single-shot) sensors. The continuous-signal sensors can be of the DC, DC voltage, e.m.f., AC voltage and pulse type. The discrete-signal sensors can be digital, positional and code-pulse sensors.

Scanning-type data logging. As illustrated in Fig. 4.4, by the commands from the control device or a timer the sensors are sequentially connected by the switch to the group normalizing converter (NC). It converts the signal into DC voltage, e.g. by rectifying AC, and gains it (brings to the unified level). The analog-to-digital converter (ADC) transfers the signal to the digital form (binary digital signal). The signal is usually converted into the digital form at the beginning of its path immediately after unifying, since the sub-

sequent processing of the digital signal does not imply a noticeable error. After the data are loaded, the computer starts the initial processing: functional conversion of signals (linearization) and scaling, which makes it possible to find the primary value from the secondary

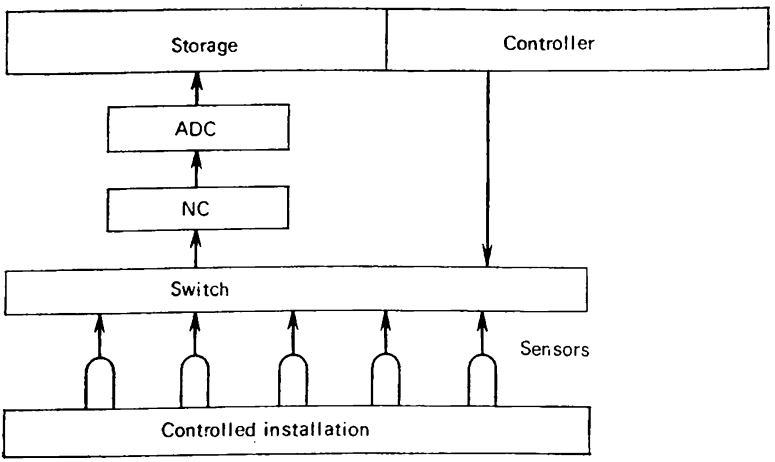

Fig. 4.4. Scanning-type data logging at power plant
NC—normalizing converter; *ADC*—analog-to-digital converter

unified measurements. The control device connects the next sensor to NC and the cycle is repeated. The scanning cycle time is

$$\tau = \sum_{i=1}^{m_g} (\tau_c + \tau_a + \tau_d)_i \, m_s$$

where m_s is the number of the similar sensors in the group; m_g is the number of the groups; τ_c, τ_a, τ_d are respectively the times of connection and operation of the normalizing converter, analog-to-digital converter and the time of delay between the conversion of the signal and the subsequent changeover of the switch.

If the number of the sensors is too large and the scanning time is impermissibly long, several converters and switches are installed. The total scanning speed is determined by the number of the sensors and their scanning speed, available time of the central processor and the production requirements.

To collect and transmit real-time dispatch information in the power industry, use is made of the communication channels and equipment, telemetry and data transmission facilities.

The communication channels used in the power industry can be of the wire, cable, radio-relay or RF (via transmission lines) type. The same communication line can be utilized for transmitting various

messages—telephone, telegraph, telemetry, etc. The messages are transmitted in the burst, time-sharing or frequency-sharing mode to ensure a rational use of the communication line. There are three modes of transmitting information via the communication channels: a simplex mode when the information is transmitted to one direction only and one channel is needed, a duplex mode with a simultaneous transmission in both directions — two channels are needed, a half-duplex mode with an alternate exchange of information or transmission of main information to one end and receipt of the service information from the other end — two channels are needed, one of which may be low-speed.

The existing communication network of the Minenergo (Power Industry Ministry) of the USSR comprises RF communication channels established via the transmission lines, AF aerial and cable communication lines for the power plant-to-power system and distribution network communication. At the power system-ACB and ACB-CCD levels, use is additionally made of the leased channels of the Ministry of Communications as well as of RH cable and radio-relay lines. The teleprinter communication at all the levels is based substantially on the subscriber's telegraph network of the Ministry of Communications.

Telemetry devices (TMD) in MCS. TMDs are intended for automatic collection and transmission to the controlled installation of the data on the status of the switching gear (telesignalling—TS), current values of the variables (telemetering—TM), and transmission of the control signals (telecontrol — TC, teleregulation — TR, teleinterlocking — TI). The telemetry devices can perform either one of or several such functions, e.g. TC-TS, TM-TS, TC-TS-TM, etc. (combined telemetry devices). There are single-channel telemetry devices which transmit information from one sensor via one telemetry channel and multi-channel devices which use the channel in the time-sharing mode to transmit information from a group of sensors, analog (continuous) and discrete (code-pulse) telemetry devices.

The telemetry systems comprise devices arranged at the dispatch office (DO) and controlled stations (CS) interconnected by channels. The systems may be single-level or multi-level. The single-level systems are distinguished by the number of the devices at DO and CS. The most promising devices for telemetry communication in PP and PS MCSs are the combined multi-channel code-pulse devices.

Telemetry device structure. A simplified structure of such a device is shown in Fig. 4.5. It comprises two half sets: a transmitter and a receiver. Connected to the input of the telemetry transmitter are sensors R (contacts of the position repeaters) and S (contacts of converters for converting measured power, voltage and current to the normalizable signal). The analog signals are alternately scanned and

converted by the analog-to-digital converter to the serial binary-coded octal code. The discrete signals are encoded by the discrete data sink (DDS). The word blocks are transferred to the encoder (E). Here a special protection element is added to the information elements. From the encoder the information is fed to the line adapter

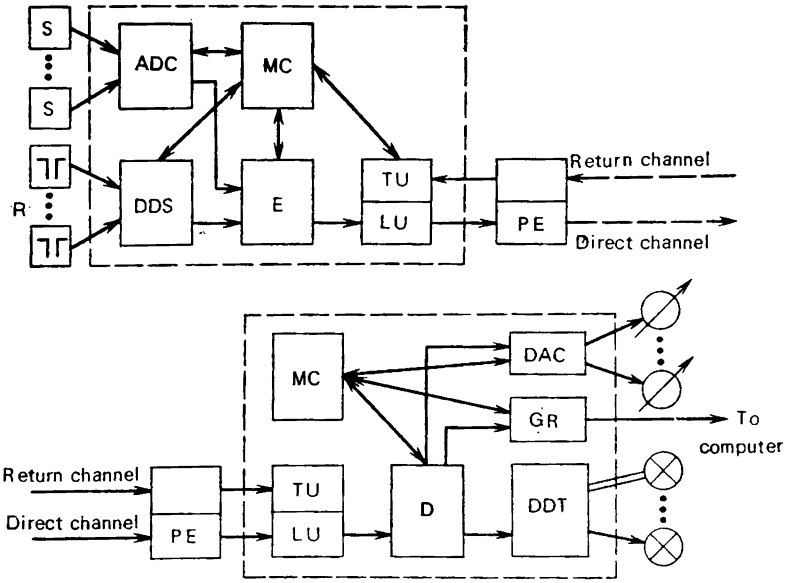

Fig. 4.5. Telemetry device structure

S—analog signal sensor (converter); *R*—relay contacts; *DAC*—digital-to-analog converter; *DDS*—discrete data sink; *DDT*—discrete data transmitter; *E*—encoder; *D*—decoder; *MC*—mode controller; *LU*—line adapter unit; *GR*—group register; *PE*—packing equipment; thick lines show information links, points show control links

unit (LU) and then to the secondary packing equipment (PE), the AF signals are converted to the RF modulated signals for transmission via the telemetry channel.

At the receiving end the RF signals are demodulated in PE and are relayed through LU to the decoder (D) which verifies the received information. If no errors are detected, D transmits the information according to the flags and addresses either to the digital-to-analog converters (DAC) or to the discrete data transmitter (DDT) for the signal elements, or to the group register (GR) to which the input modules of the computer are connected. The telemetry device is controlled by a controller which sets the operating cycle, synchronizes receipt and transmission, etc.

Data transmission methods. There are two methods of data transmission: a cyclic method and a sporadic method. In the cyclic method the entire data array is retransmitted after a certain period of time

(cycle). In the sporadic method only the changed signals (variables) are transmitted. One direct channel is enough for the cyclic transmission, while the sporadic technique requires a direct and a reverse channels (service signals are transmitted).

In cyclic transmission, the sink traces and rejects the message with a transmission error. During the next cycle the transmitter sends the same message again. If a message is rejected in a sporadic transmission, the information is lost. After sending the sporadic message the transmitter retains it in the memory till the acknowledgement is received. The acknowledgements are transmitted via the reserve channel. If no such a channel is available, the message is resent by the transmitter till the acknowledgement is obtained. If the reverse channel is in failure, the telemetry device automatically changes over to the cyclic mode. When the transmission cycle is to be performed once, e.g. after debugging, the sink generates a special request. Generation and reception of these signals as well as the test of the reverse channel are carried out by the test units (TU).

The cyclic telemetry devices are more reliable and simple, however, if the amounts of information are great, the transmission time increases because both the useful (changed) and redundant (unchanged) data are transmitted (this is particularly disadvantageous with TSs which change but seldom). The most of the modern telemetry devices are adapted for the cyclic transmission of TMs and sporadic transmission of TSs. To increase the reliability, provision is made for automatic selection of the operable channel (if two direct channels are available). Some telemetry devices feature TS and TM transmission on request.

The telemetry devices use the byte (eight-bit) information transmission structure. TMs and TSs are sent in groups (minor cycles) and each group may contain information on one or several TMs or TSs. The structure of the minor cycle differs with telemetry devices but it always includes the beginning code, the address code, the information bytes, the protection code. For instance, for the telemetry device, type ТИ-512, the TM minor cycle comprises 19 bytes: 1 byte is the beginning code, 2 bytes are the inversion address code, 16 bytes are the inversion information of eight TMs. One minor cycle of TS includes 5 bytes: 1 byte is the address code, 2 bytes are the beginning code, 2 bytes are the information of eight TSs.

Trends in telemetry development. The main trend in the development of the telemetry equipment is the utilization of microprocessors built in the telemetry devices. This makes possible to process data for excluding the messages which carry no useful information (packing methods); use lower-level processing, thus making the computer of the higher control level free of routine operations; perform the functions of the local automatic and on-line control and monitoring devices.

Data transmission equipment. To increase the validity and speed of transmission of the alphanumerical information, the automated management and control systems use the data transmission equipment (DTE).

The diagram of connection of the data-use point with the computer is shown in Fig. 4.6*a*. The DTE set consists of two half sets. A half

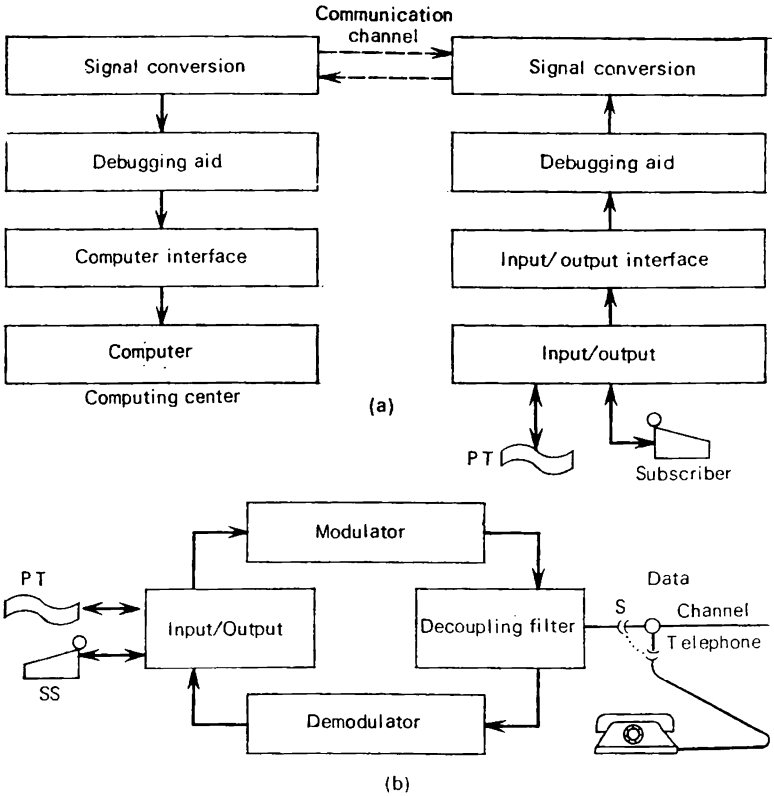

Fig. 4.6. Connection of data-use point with computer
(*a*) connection of subscriber with computer complex; (*b*) diagram of stationary modem

set includes a device for converting a signal into a form most suitable for transmission over a given communication channel and repeatedly converting the received signal. The signal conversion (modulation and demodulation) is carried out by a special device called modulator-demodulator or shortly modem. The communication system also includes a debugging aid (hardware or software) and an adapter (interface) for connecting DTE to the channel. The I/O unit may be an alphanumerical printer or typewriter, a card or tape punch, an operator CRT screen or signal transmitters (sensors).

To establish communication, a telephone set is used. The call is made manually or automatically, by the computer. After the communication is established, switch S (Fig. 4.6*b*) is shifted from the TELEPHONE position to DATA and the information is transmitted or received. For convenience in use the telephone channel is divided into two subchannels, one of which is used to transmit the data from the subscriber's set to the computer, the other in the reverse direction. The data transmission speed varies. The zeros and ones are represented by signal elements of different frequencies.

Debugging. To locate and eliminate errors in data transmission, use is made of hardware debugging aids or extra (redundant) data. To increase the validity, the information to be transmitted is divided into messages usually consisting of 240, 480 or 900 bits. The methods of verification of the information are diverse. Various DTE are manufactured in this country. The DTE set includes a receiver and a transmitter for two-way data exchange in the half-duplex mode via a switched or non-switched telephone channel with a speed of 600 and 1200 bauds. In addition to a direct channel DTE requires a reverse low-speed channel (75 bauds) for its operation.

The main units of DTE are I/O devices on five- and seven-track punched tape, a controller, a storage device (SD) with a capacity of several (at least two) messages from 240 to 960 bits, a debugging aid (DA), a control panel with a telephone set and a modem for connecting DTE to the communication channel. The punched tape with the information to be conveyed is set into the punched tape reader, the operator at the transmitting end contacts the operator at the receiving end over the telephone and starts the transmitter. Two messages are read off the punched tape to SD and the first message is sent to the sink. After verifying the data the receiver transmits the acknowledgement, SD obtains the third message, while the second one is supplied to the channel and so on. If errors are located, DA of the receiver sends the request for repetition and the transmitter again conveys the same message. After several unsuccessful repetitions the transmission ceases and a signal is supplied to the operator. The operating principle of DA is similar to that of encoder-decoder (ED) of the telemetry equipment.

At the receiving end the information is output on the punched tape available for the computer. If necessary, the punched tape can be printed out on a teleprinter. There are means for connecting an automatic-high-speed printer to DTE so that the information can be received and tabulated concurrently. Special adapters provide for connecting DTE to the display. The information prepared on the display screen is transmitted to DTE. A direct input of the information from DTE to the computer is also possible. In such a case DTE becomes essentially a remote subscriber station of the computer.

The next stage of the data collection system is the creation of

a network of subscriber stations (SS) linked with the central computer by the communication channels. A wide variety of SS facilities are manufactured for operation with the third-generation computers, ranging from simple devices functionally similar to DTE to complex computerized terminals.

4.5. Teleprocessing and Daily Scheduling

Focus our attention at problems of organizing telemetry data processing and using them to control operation of power plants.

Data collection system. The data are collected by the real-time information complex (PS MCS RTIC). The system of collecting, processing and representing information for the dispatch control points (IS) operates in the real-time mode and ensures automatic input of telemetry data into the computer, processing, file generation, on-line variable representation and logging, data exchange between the machines and transmission to the computer complex (CC) for planning calculations or use at a higher management level. Several types of ISs exist today.

Consider the general organization of IS. The entire process may be divided into five stages: input of telemetry data, primary processing, secondary processing, editing and complementing by the dispatcher, documenting and storage of files. Let us consider all these stages.

The data can be set from different telemetry devices. The information system developed by the All-Union Research Institute of Electronics allows setting up to 250 telemeasurements and up to 2000 telesignals into computer EC-1010Б. These figures will increase twofolds in the future. The telemetry data input is initiated by the computer scanning the variables of TE or by the interrupt signals fed from TMDs. Machines CM-1, CM-2 or unified system machine EC-1012 can be used for the purpose within the framework of PS MCS. All these computers are adapted for such an application and have the required software.

The primary processing is cyclic, e.g. with an interval of 1 s. It includes:

(a) conversion of the format and address of the message. The message formats are converted into a unified form — a binary-coded octal code without a sign. The absolute address of the message is replaced with a symbolic machine address;

(b) smoothing (averaging) of readings to exclude random surges (overshoots) of the variable being measured. The so-called exponential smoothing is performed according to the formula

$$z_{j,i+1} = \gamma x_{j,i} + (1 - \gamma)\, z_{j,i}.$$

where γ is the constant; z is the smoothed value and x is the measured value of jth measurement obtained at a given $(i + 1)$th and preceding ith measurement step;

(c) data verification. The valid telemetry data are those the value of which does not change considerably (because of the sluggishness of the processes) in two successive measurement cycles. If no error exists, the difference between teledata in two cycles is less than the maximum permissible deviation: $| x_{i+1} - x_i | \leqslant \varepsilon$. Limit ε may be constant or adaptive. If limit ε is exceeded, the information is not destroyed but gets a reject flag. Such an information is used if no more accurate data are available. TSs are verified by a double confirmation of the signal of the changed position of a switching device;

(d) data packing. If a new $(i + 1)$th value of variable x_j is slightly different from the preceding value

$$x_{j,i+1} - x_{j,i} | \leqslant \varepsilon_1$$

where ε_1 is the required accuracy of the variable evaluation (usually $\varepsilon_1 \neq \varepsilon$), the new value is not displayed, thus excluding frequent changes (blinking) of digital readings;

(e) TM scaling is the process of converting the measured value into the actual units. The output curve of the TM device is assumed linear and the scaling is performed as follows

$$z_j = A + Bk_j$$

where A and B are the constants; z_j is the calculated value of the jth variable; k_j is its code received from the TM device;

(f) process monitoring. The physical value calculated by the telemetry results is compared with the process upper and lower limits. These limits should be adaptive. Usually two constant process limits are assigned: an emergency limit and a warning limit. As the process variable falls beyond said limits, the dispatcher is warned by a signal and the variable value and malfunction duration are printed out.

The bulk of information from the telemetry devices arrives in the numerical form (codes from 0 to 256). The code value is immediately compared with the permissible limits. If the limits are surpassed, the measurement is rejected. Should the data exceed the limits in the next cycle again, the information is retained and the reject flag is given to it.

Process signalling. If any of the process variables x_j is outside the permissible limits (Fig. 4.7) special signals are transmitted to the dispatcher. There are two process limits: warning limit *Wrn* and emergency limit *Em*.

The warning signal is fed in a certain period of time t_d (e.g. one minute) after the violation, the emergency signal is supplied immediately. If the value being monitored rises drastically (curve *1*), only the emergency signal is fed (point B_1).

When the value rises slowly only a warning signal (point B_2 on curve *2*) or both warning and emergency signals (points C_3 and D_3 on curve *3*) can be supplied.

Usually the scanning cycle initiated by TMD is sufficiently long, e.g. 3 s. The telesignals are displayed after double confirmation (6 s) and an additional delay of 4 s. Thus, each signal is displayed after 10 s. This means that the computer does not inform the dispatcher, if the scanning cycle reveals no malfunctions but documents it on the printer. It is assumed that only smooth changes in the operating conditions are of interest for the dispatcher.

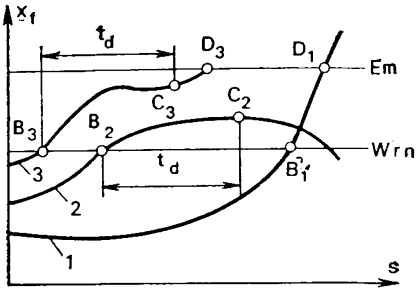

Fig. 4.7. Emergency and warning signalling
B—moment of violation of warning limit; *D*—ditto of emergency limit; *C*—actuation of warning system

The information smoothing described above is based on the same principle. If a sharp (but permissible) surge occurs with some variable, it is smoothed (filtered) in view of the available preliminary data (file).

The secondary processing is accomplished cyclically on a preset time interval (e.g. 0.5 min). The secondary processing involves preparation of the intermediate files, complementing of the primary processing data with constants and recording of the resulting information on the disk. A list (array) of TMs, a TS file and emergency TM list are formed on the disk. The lists should be so compiled that when the storage overflow occurs, the new values are written in place of the old ones.

Manual input and editing. This data processing level includes the edit and exchange programs. These programs utilize the information which is manually input by the dispatcher. Manual input of data received by the PS dispatcher over the telephone will hold a considerable place in the total amount of information for a long time. The dispatcher loads the computer using the display keyboard. Provision should be made for simple input and verification of such data (e.g. logical limits, information completeness checks and the like). After the manual input and editing, the files are converted to a form available for display or print-out, filing or transfer to other levels (other computer).

Lists and master files. The machine generates a separate schedule (list of switchings) where all TSs changed since the beginning of the day are automatically written. Provision is made for automatic generation of the list of TMs which fell outside the process limits with

indicating the time of the occurrence (TM emergency lists). The files with different averaging cycle, e.g. 0.5 s during 1 min, 1 min during 1 hour, one hour during a day, are generated to provide retrospective information. The first two files are erased as they become obsolete, while the last file is not destroyed.

File protection. The collected files will be used by different services of the electric power plant and the entire power system. All the users except the dispatchers may only read the contents of the master files and real-time documents and are not permitted to make any entries. These users should utilize an incomplete language which prohibits the input of data into the computer.

Data representation. The information loaded into the computer and processed in it may be represented on a display screen. Most frequently used for the purpose are the alphanumerical displays. The data are displayed in a standard pre-arranged form, e.g. a form of the daily schedule. The information can be also graphic, e.g. in the form of a power system diagram with indicated values of power flows along the lines and the voltages at nodes. On both occasions, each index has its fixed pre-arranged place in the form and only the contents of the information are subject to change. A part of the data is introduced into the daily schedule automatically from TMDs, the other part, manually by the operator.

4.6. Organization of Dispatcher-Computer Dialog

The dispatcher-computer dialog is effected with the aid of a special conversational system which is included in IS. The conversation is carried out in a particular language through a display. The display represents information requested by the dispatcher, while the emergency signals are displayed automatically. The dispatcher can manually call the list of emergency TMs or TSs of the equipment which changed its position, etc.

Dispatcher commands. The man-machine dialog requires a simple language which would not demand special knowledge on the part of the dispatcher. Usually this is a command (macroinstruction) language. The commands can be input by the operator in separate characters on the display keyboard. For instance, a command may look as F-3-12. It is possible to provide a particular set of functional keys such as "daily schedule call" key. When such a key is pushed, the respective program will be initiated. The macroinstruction language is simple and convenient for the dispatcher. The set of commands depends on the local conditions and may vary widely.

The list should contain the following groups of commands:

— the commands informing the dispatcher of the potentialities of IS; these involve calling the lists held in the computer memory,

e.g. the list of commands available for the dispatcher, the list of standard forms existing in the system, the list of the controlled installations with their designations, the list of designations and meanings of TSs and TMs, etc.;

— the commands for calling the tabular information; these involve calling a particular table of TSs or TMs, master file and historical data;

— the service commands, i.e. those for storing (printing) some data, clearing wrong data or page, paging some schedule forward and backward, tracking any variable which is of a particular interest for the dispatcher and printing its values after a preset time interval. The end-of-line symbol is also a service character.

For instance, to generate a daily schedule, the following main instructions are needed:

1. Call of the standard form (F) schedule of a given type to the screen for reading (the command may be F-N, where N is the concrete number of the schedule).

2. Call of v of the same form for filling in the next line or updating some data (for example, F-N-v-tt, where tt is the line number).

In these commands N and tt should have a particular numerical value. The second instruction should not be available to all the users so as to avoid inadvertent distortion of the information.

3. Form print. The command is as follows F-P-N.

Divide all the forms held in IS into two types: one type is fully filled in by the computer, the other requires manual data input. A separate file is organized for each form of the first type. It is replenished from the current line files in view of the data input by the dispatcher. After the current line is completed the daily schedule file (DSF) is transmitted to the data bank. Besides, the daily schedule printing file is created (accumulated continuously). A possible variant of the functional keyboard of the dispatcher display is shown in Fig. 4.8*a*.

Filling in daily schedule. The algorithm of the conversational system operation for compiling the schedule is shown in Fig. 4.8*b*. At the ith hour (e.g. at the tenth hour) the dispatcher calls the required form for a given jth installation and, e.g. the following data appear on the screen:

Hours	Power plant		Flow No. 1	Flow No. 2	Consumption	Power loss
	No. 1	No. 2				
8	390	150	250	500	768	12
9	380	140	200	400		
10	360	▽	350			

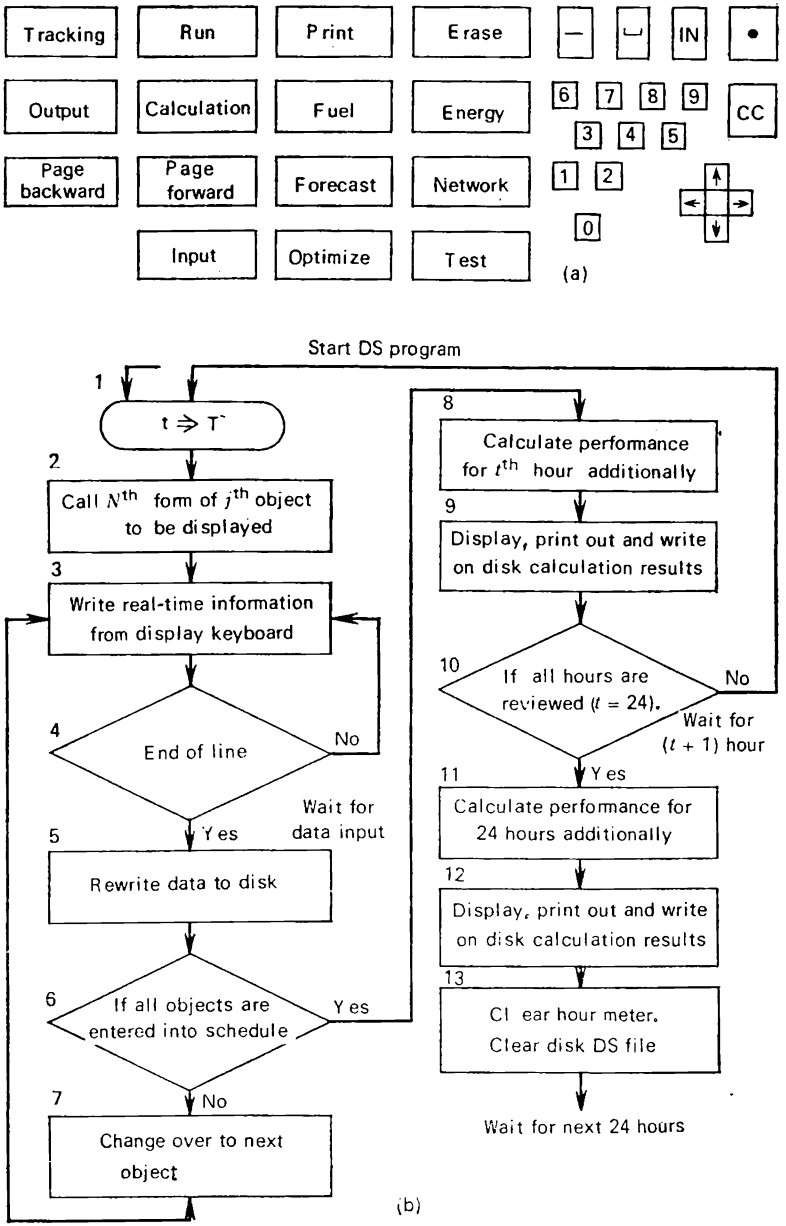

Fig. 4.8. Organization of dispatcher-machine dialog

(*a*) example functional display keyboard of PS CC; FUEL, ENERGY, FORECAST, NETWORK, TEST are conventional names of problems; the right-hand part of the figure shows the digit keys, shift keys and some service keys; (*b*) algorithm for filling in daily schedule

To show the trend, the screen also displays two preceding hours (the 9th and 8th). Assume that power plant No. 1 is equipped with a telemetry system and power plant No. 2 is not. The data for power plant No. 1 are introduced into the table automatically and the marker (symbol ▽) indicates the point from which the information is to be input manually. The dispatcher writes in this column the data on the load of the second power plant received over the telephone. Assume that the load is 130 MW. He inserts the information manually by depressing keys 1, 3, 0 (Fig. 4.8*a*) successively. As each figure is input, the marker automatically displaces one position rightward. The power of flow No. 1 is obtained automatically and the dispatcher passes it by gradually displacing the marker. Next he manually inputs the data on flow No. 2. This ends the 10th hour filling-in procedure and the dispatcher confirms it by a special end-of-line key. The information is written on the disk. After the last form is filled in, the required operation variables are calculated (e.g. total consumption of electric power or power loss in networks) and the fully generated line of the daily schedule is displayed on the screen, printed on a printer and written on the disk. The last algorithm blocks check if all the hours of the day are reviewed, organize the necessary additional calculations, printing of the daily schedule, its storage and change-over to the next day.

Some additional capabilities. In the course of work a need may arise to modify the data of some past hour (e.g. the calculated data changing the value of a power flow are obtained). To perform such a modification, the dispatcher pages backward the daily schedule or the respective form to find the required hour, modifies it and returns back to the current time. The program performs all the necessary calculations and introduces corrections. If the data received over the telephone differ from the telemetry information and the dispatcher regards the telephone data more reliable, he writes them in place of TMs. Further these manually input data, rather than TM data, are used in the calculations and inserted into the file.

Sometimes the data from an installation are not received up to the end of the astronomic hour. In this case the dispatcher selects the time prolongation (waiting) mode. Such a mode can be engaged automatically, if there are no data required to complete the calculations, i.e. the end-of-line key is not depressed.

If the data input by the dispatcher are to be used in different documents, they are automatically introduced into all the forms as many times as required.

System adapting. The teledata processing system should allow for change of the document form or introduction of new forms whenever necessary. It should be capable of expansion, i.e. be adaptive to the varying external conditions.

4.7. Automated Process Control System of a Thermal Power Plant

Goals of APCS. There are seven basic goals of APCS of power stations:

— monitoring of the power generation process;
— stabilization of process and electrical variables;
— program control (e.g. start and stoppage of the equipment);
— optimization of operating conditions;
— protection against accidents;
— real-time communication with the upper management level;
— documentation (real-time printing).

Stages of APCS implementation. Four stages of APCS implementation may be distinguished. At present, only the first and the second stages can be encountered.

1. Adviser machine. The computer is not included in the control circuit; all the control operations are carried out by the operator.

2. A computer is a superstructure over the existing local automatic control devices. Control is effected by changing settings of the local automatic control equipment.

3. A computer is a superstructure over specially created digital local control devices (e.g. minicomputers functioning as local regulators).

4. A cybernetic system in which local control devices are coalesced with the central processors to form a single cybernetic system.

APCS classes. APCS is usually divided into several classes. Each class (except the zero class — program control of machines and mechanisms) covers a definite number of the controllable (recorded) variables: the 1st class up to 20, the 2nd class up to 40, the 3rd class up to 100, the 4th class up to 800 variables.

Higher classes of APCS are used to control the production process as a whole: the 5th class is employed when a control system is not equipped with a subordinate computer; if such a computer is provided, the 6th class is used.

Communication of operator with computer and installation. Organization of the communication of the operator with the computer and installation is very important for APCS. The operator has no time for programming when using a computer in the real-time mode. He addresses the machine in a special language close to his natural language and available for the computer. To achieve this, the APCS computer should be provided with appropriate translators. Conversation is usually carried out by the question/answer dialog with the aid of a display (screen). The development of such a language is an important stage in the creation of APCS. Used most frequently for the purpose are the command language and the functional keys of the display.

APCS of power-generating units and plants are based on the information system or information complex (IC) which executes the functions of centralized control—collection, primary processing and representation of information on the process variables and status of the process equipment. IC also performs signalling of the process conditions and logging (printing) of variables.

The organization and operating principle of IC are similar to the data collection principles outlined in Section 4.4. The difference resides in that the information is inserted into the computer from the sensors which are located not far from the computer, so that no TMDs are needed.

The system monitors and records deviations of the process variables from the preset limits, operation of the interlock and protective devices.

Sophisticated APCS computes the technical-and-economic indices of the power-generation process, prepares information for higher control levels. Automatic control functions can also be performed. Cooperation between the computer and the local automatic control devices is vital for APCS. APCS IC of a power-generating unit can be used as an information base for APCS of the entire thermal power plant.

APCS hardware of the power-generating unit is diverse and can be built with the use of both special- and multi-purpose computers. The first power-generating units were equipped with special-purpose machines of the ИВ-500 class (Fig. 4.9*a*).They had very limited capabilities and small memory. Later the so-called "Complex-BBCS" was installed; it was a special-purpose computer for the power-generating units assembled of typical elements of the building-block computer series (second generation). The machine performed the functions of the centralized supervision. At present, a more sophisticated special-purpose machine, type M-60, is developed. It is intended for operation with the 500-MW sets, executes the same functions as the "Complex-BBCS", but is comprised of the third-generation BBCS elements.

The information complex alone is insufficient for rational control of the thermal power plant. Therefore, a superstructure in the form of a special-purpose computer complex (CC) was erected over the information system of the power-generating unit to solve various MCS problems. CC is usually based on computers, class M-6000 or M-7000. Organization of the IC + CC complex put forward a number of problems. The methods of integration of the two complexes is greatly dependent upon the MCS type. For instance, machines "Complex-BBCS" and M-6000 do not permit a direct interconnection; therefore, a special adapter, rather intricate and expensive, was developed.

Apart from servicing the power-generating units, the M-6000

computer handled the general problems of TPP MCS so that the integrated management control system was gradually formed.

The development of small computers and the advent of universal devices for connection with the installation make it possible to create a united information-computing complex. It performs the information functions for the power-generating sets and calculations both for each set and for the entire power plant. If the power plant

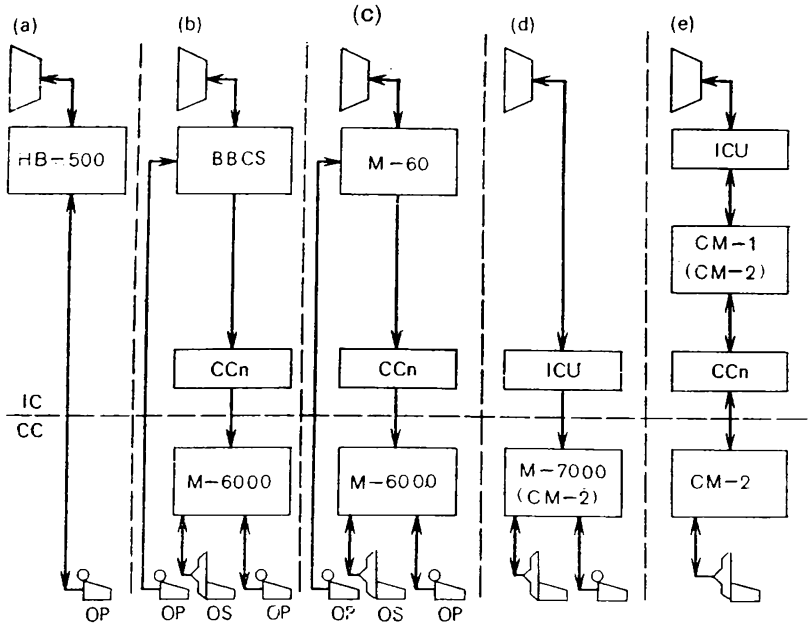

Fig. 4.9. Variants of TPP APCS hardware

(*a*) НВ-500 information system; (*b*), (*c*) information-computing complex based on special-purpose machines (BBCS and M-60 computers); (*d*) integrated single-level system (IC + CC); (*e*) two-level system

has a great number of sets, multi-level (usually two-level) systems (Fig. 4.9*e*) can be used. The lower-level machines serve from two to four sets each, while the upper-level computers carry out the general management and control operations for the entire power plant.

Data input into computer. There are four typical methods of data input:

1. Automatic input from sensors.
2. Manual transfer of the incoming document to the machine medium (punched card, magnetic tape) and input into the computer.
3. Teleprinting input in the "tape-to-tape" mode. The document is set on the teleprinter keyboard. At the receiving end, the information is output in the form of a document and punched tape (PT). PT

is manually inserted into the computer. The calculation results are output on PT and are transferred to receiving PT by the teleprinter.

4. Automatic input with the aid of the data transmission equipment (DTE). It is the development of the previous method. The subscriber station (SS) is connected by DTE to the computer. The data are input directly to the machine and the results are conveyed immediately to SS.

There are numerous examples of thermal power plant APCSs. APCS of the district thermal power plant with 200-MW power-generating units comprises four subsystems: process control, real-time control, analysis of technical-and-economic indices, and management and accounting. Let us consider the first three subsystems.

The process control subsystem solves purely informational problems. It supplies information on the process conditions to the set and plant control panels and to the management of the power plant at the preset intervals and prints out the required data after every 15 min.

Each 200-MW unit inputs up to 90 analog and digital signals. It is planned to increase this number to 177. Among the parameters being measured are the temperature, pressure, medium consumption, consumption of power for own needs, content of oxygen in flue gases, power generation per set. Scanning of the sensors and averaging of the data are carried out every 30 s (rapidly changing variables) and 2 min (slowly changing variables).

The real-time control subsystem solves two problems: plotting of energy curves of the equipment and differentiated distribution of loads among the power-generating sets.

The subsystem for analysis of technical-and-economic indices (TEI) calculates TEIs of the power-generating sets in real time and averages them for an hour, shift, week, month; periodically analyzes TEIs with generating recommendations for optimization of the rated parameters, evaluates effectiveness of the shift personnel, processes the equipment test results.

The shift personnel effectiveness is evaluated to check extra losses caused by suction of air to the boiler, insufficient vacuum in the turbine condensers, excessive temperature of flue gases, insufficient temperature of feed water, leakage of steam and condensate. To this end, the above-mentioned parameters are measured and compared with rated ones and then the additional losses (economy) of fuel are calculated.

The management and accounting subsystem compiles various forms of technical and finance activities, including payrolls, and keeps a record of incoming fuel. The last task is of a particular interest for us because it is intimately associated with the problems of optimal operation of TPP. The real-time fuel delivery and consumption with respect to grades are accounted and the respective documents are

printed out. This makes it possible to perform real-time calculations of the fuel component in the power generation cost, estimate the fuel quality and its utilization factor. The solid fuel and fuel oil balances are compiled for a day, from the beginning of the month and for a month.

4.8. Hydro Plant Management and Control System

Problems of HP MCS. All the problems of HP MCS may be conventionally divided into four groups: "Water"—the problems of advantageous utilization of water resources; "Power"—the problems of rational supervision of generating sets; "Information"—the problems of information; "Economy"—the problems of accounting, technical and economic planning, economic activity.

Listed below are the main types of the problems less the economic ones.

Information. 1. Collection and recording of information on the performance and status of the main and standby equipment under normal and emergency conditions.

2. Representation of information.

3. Statistical analysis.

4. Organization of accounting of electric power generation and auxiliary power consumption.

5. Compiling and printing of documents.

6. Setting of reference files on machine media to hold information on operation of the hydro plant.

7. Adaptive refinement of energy characteristics of the generating sets and hydro plant, characteristics of the head water and tail water, head losses in water conduits, etc.

8. Adaptive refinement of plant security constraints.

Water. 1. Optimization of long-term regimes of the water reservoir of an isolated hydro plant.

2. Calculation of hydro plant powers according to the preset load schedule.

3. Calculation of water reservoir levels for known load schedules and domestic use.

4. Plotting of water control graphs.

5. Reservoir routing.

6. Optimization of complex use of water resources in long-term regulation.

7. Correction of the water reservoir regime on the basis of the source information forecast.

8. Optimization of daily regime of the water reservoir.

9. Correction of water discharge and head/tail water levels at daily and weekly regulation of runoff according to the source information forecast.

10. Calculation of non-steady regime at daily and weekly regulation.
11. Modeling of hydrographs.
12. Calculation of water balance.
13. Analysis of effectiveness of water resource utilization.

Power. 1. Selection of power-generating sets and their active powers for the period of planning.
2. Selection of power-generating sets and their reactive powers for the period of planning.
3. Distribution of the active and reactive power reserve among the sets and groups of sets of the hydro plant for the period of planning.
4. Elaboration of a schedule for using auxiliary mechanisms for the period of planning.
5. Preparation of programs for controlling the power plant in pre-emergency, emergency and post-emergency situations.
6. Calculation of settings of relay protection and automatic equipment.
7. Selection of the switching system for the plant.
8. Real-time updating of the planned availability of power generating sets under normal conditions.
9. Current regulation of active and reactive powers of separate sets and entire plant under normal conditions.
10. Real-time updating of the value and allocation of the standby powers of the plant.
11. Frequency control.
12. Voltage control.
13. Analysis of pre-emergency status of sets, plant and power system.
14. Programmed redundancy of the relay protection, automatic and signalling equipment.
15. Function tests of sensors.
16. Plotting of equivalent energy curves of the plant.
17. Analysis of effectiveness of generating set operation.

The HP information sources are divided into six groups: the water reservoir (head water), water-development works, power house, step-up substation, tail water and external sources. The information sources and types are indicated in Table 4.1. Note that a part of information arrives continuously from the sources while another part is constant and is relatively seldom set into the information system or modified.

The first group of information is usually termed the real-time information, the second group, conventionally constant or normative-reference information. Not all the sources give information vital for operation of the hydro plant. For instance, the water structure measurements are made relatively seldom, they are used only to check the structure conditions. The electric equipment temperature is indicative of its condition; if the equipment is properly designed

Table 4.1

Information Sources at HP

Point of measurement	Parameters to be measured
Water reservoir (head water)	Levels, discharges and velocities of water; ice thickness, water temperature; prevailing wind direction and speed
Water-development works	Static levels; seepage, infiltration pressures; deformation and settlement; stresses; velocities of discharges; spillway (gate) condition
Power house	Equipment condition; water flow rates; temperature at characteristic points of equipment; electric parameters; condition of relay protection and automatic equipment; sequence of operations and operate parameters of protection and automatic equipment; opening of turbine distributors; incidence of wheel blades; vibration, stresses; cavitation; pressure in receivers, pressure at characteristic points of auxiliary lines; jet transducers
Substation	Electric parameters; temperature at characteristic points of equipment; condition of equipment and circuitry; condition of automatic and relay protection equipment; sequence of operation and operate parameters of protection and automatic equipment
Tail water	Levels, discharges, velocities, ice thickness, length of air hole
Economy subsections	Plans, material transfer data, accountancy, etc.
External	Load and voltage schedules; hydrological forecasts; meteorological situation; system constraints; system equivalent characteristics

and normally operated, the temperature affects but slightly the operation of the power plant. On the contrary, such variables as water levels, discharge values, equipment status, load curves, hydrologic forecast, conditions of the relay protection and automatic equipment are essential for optimal operation of the hydro plant.

According to some estimates for HP with n generating sets and m transformers, the total number of measurements is equal to

$$n_{\text{meas}} = (30\text{-}40)n + (15\text{-}20)m + (50\text{-}100)$$

Real-time information at HP. The real-time information is conventionally divided into three groups: the process information, the equipment information, the statistical information. The measurement cycles (in seconds) may be estimated as follows: power flows over aerial transmission lines—3; voltage levels—20; generating set power—10; temperature—up to 30; discharge—up to 30; the equipment

information is collected sporadically as required; the sequence of operation of the relay protection and the parameters at the moment of operation—up to 0.1 s.

4.9. Management and Control System for Electric Network Facilities and Substations

The management and control system for electric network facilities (ENF MCS) is a man-machine system which ensures automatic collection and processing of information with a view to improving effec-

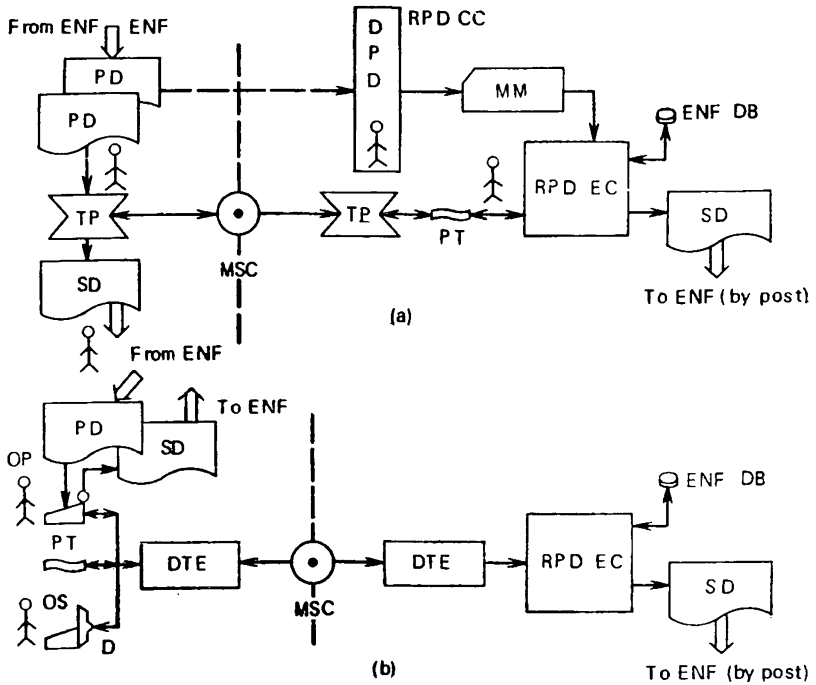

Fig. 4.10. Simplified diagram of ENF MCS hardware without integrated computer

(*a*) subscriber station with teleprinter; (*b*) subscriber station with data transmission equipment; *OP* (*OS*)—operator panel (screen); *DPD*—data preparation device; *PD*—primary document; *SD*—secondary document; *MM*—machine medium; *ENF DB*—ENF data bank; *MSC*—message switching center

tiveness of the ENF operation and reliability of power supply at a rated quality of electric energy. ENF APCS is a lower-level component of power system MCS.

ENF MCS hardware. Large computers are usually unfeasible with ENFs; therefore, the latter will be equipped with subscriber stations (SS) without computers or SSs with small computers.

The *subscriber stations without computer* can be of two types (Fig. 4.10).

A. Teleprinter SS. At the initial stage of building ENF MCS no complex computers are needed. To obtain first results and inculcate habits of using the computer for solving the management problems upon the personnel, it is sometimes sufficient to install a teleprinter at ENF. The information manually input at ENF is received by the teleprinter installed in RPD CC in the form of a punched tape. The operator inserts this tape into the computer for processing. The calculation results are output also on a punched tape and are transmitted back to the teleprinter installed at ENF. Such an operation of SS is called the tape-to-tape mode. The system based on teleprinters is successfully used at some ENFs in Latvia to solve the real-time dispatch control tasks.

B. Subscriber station with data transmission equipment (DTA) installed at ENF. Such a system provides for direct input of information from SS to the computer and transmission of the computer data to the subscriber. The subscriber station equipment may include a teleprinter, an electric typewriter or a combination of an electric typewriter and a display.

A bulk of the ENF information is relatively permanent and constitutes the ENF data bank. It is transferred to the machine medium (punched card) and written in the external disk or tape storage of RPD CC. To initiate processing, only a key (name) of the program needed to process or modify the source data is transmitted from ENF. The request specifies the information which is of interest to the ENF operator (e.g. the numbers of electric network nodes or lines whose operation is to be checked). The calculation results are transmitted to ENF.

ENF peripheral stations with a small computer. A small computer installed at ENF and operating in the off-line mode can handle a number of management control problems. Such a system is used in the Eastern networks of the Rostov power department where the "Nairi-K" machine calculates short-circuit currents and steady-state currents, wages, etc. A small computer installed at ENF can be connected to RPD CC by a teleprinter or DTE.

Computerization of centralized control. A small control computer can be used at the ENF dispatch office for effecting centralized control. Telemetry devices are connected to the computer through the interfaces (Fig. 4.11). The computer collects information from the external sensors and processes it initially. Then the information is displayed on the control panels or CRTs and the dispatcher is warned of impermissible deviations of the variables under check. Besides, the machine prints daily schedules and some other documents. Computerization releases the dispatcher from the bulk of routine operations (11% of the ENF dispatcher's working time are spent for collec-

ting and logging load and voltage data and 23% for making entries in records). The large substations can be automatically controlled with the use of computers.

Complete set of computers for ENF MCS. Separate large ENFs can be provided with two groups of computers: one group for real-time control, including centralized control functions, the other group

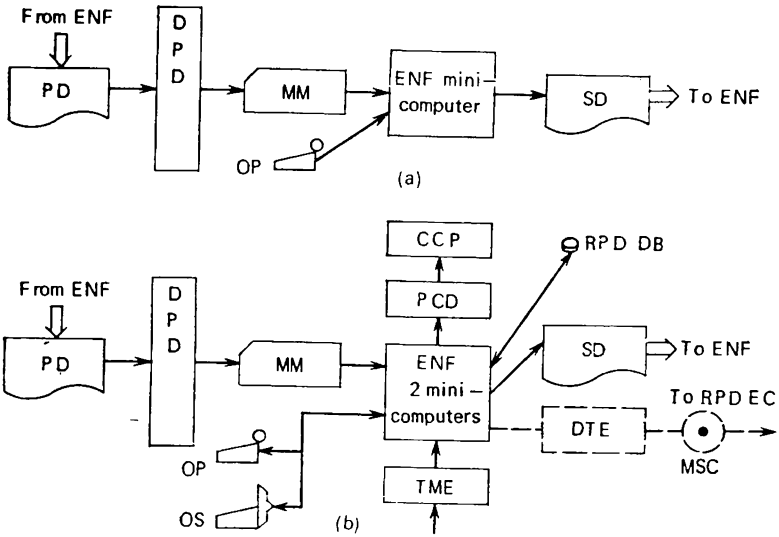

Fig. 4.11. Hardware of ENF based on minicomputer

(*a*) computer operates in off-line mode; (*b*) computer executes centralized control functions; *PCD*—panel control device; *TME*—telemetry equipment controller; *CCP*—central control panel; dotted line shows data transmission equipment which converts ENF MCS into two-level management control system: ENF MCS-RPD MCS

for planning and solving some production and economic problems. The first group of devices forms the real-time information complex outlined above, the second group, a computer complex. The computers with associated miscellaneous equipment installed at ENFs may be used to serve other enterprises (installations) of RPD (EP) and execute the functions of an intermediate data acquisition and processing point.

ENF MCS subsystems and their tasks. The ENF MCS subsystem components and functions depend on the local conditions such as the power and role of ENF in the system, the actual networks and voltage structure, the ENF management structure. In general, the following subsystems are organized: real-time (dispatch) control, equipment logging and analysis, maintenance and reconstruction management, reliability control.

ENF MCS tasks. For convenience, divide the ENF MCS tasks into six groups: information, real-time control, operation planning, computational, record-keeping and analysis of operation, management. Consider some of these problems.

Information tasks discussed above include:

— supervision of operation variables—cyclic input of data in the computer from telemetry devices, scaling, verification, warning of impermissible deviations, automatic display of data on the ENF control panel or individual dispatcher screens;

— automatic logging of digital and analog information (daily schedule printout);

— set-up of data files—storage, modification, primary processing and output of information, generating data for transmission to superior management levels.

Real-time control. These are the network supervision and control problems:

— checking of the electric network switching gear status;

— supervision and upkeeping of the network according to the duty and current instructions;

— checking of equipment loading and prevention of impermissible overloading;

— checking and regulation of network voltage;

— routine switchings;

— rapid elimination of forced outages.

The computers have not yet found wide applicaiton in the real-time control.

Planning of electric network operation. These problems include:

— determination (forecasting) of loads for network nodes for a month, week, day;

— consideration of requests for outage and repair of the network equipment, estimation of the possibilities and variants of meeting the requests;

— elaboration and updating of normal and repair schemes of the networks;

— elaboration of typical repair schemes;

— elaboration of measures to decrease power losses in the networks, optimal voltage and reactive power for them;

— determination of optimal breaking points of a distribution network for optimizing the latter to cut power and electric losses;

— elaboration of voltage regulation laws at the supply center and of settings at the voltage local regulation devices; provision of the voltage levels required by the consumers;

— logging and processing of load and voltage measurements;

— compilation of schedules for commissioning new installations and equipment (network development program).

The computers are finding extensive use in operation planning.

Computational tasks may be independent or may be a part of other tasks. They include:

— calculation of flow distribution, voltage levels and power and electric losses under various conditions of the network operation (normal, repair, post-emergency); these are widely employed, e.g. for detecting lines with maximum losses in the networks with a view to elaborating measures to decrease them;

— calculation of short-circuit currents and rated currents for fuses, settings of the relay protection and automatic equipment (RPA) at changes of the network operation variables and configuration;

— checks of the equipment for thermal stability;

— calculation of emergency underproduction of power.

The subsystem for the network equipment record-keeping and analysis includes:

— inventory of the primary electric equipment and control means;

— record-keeping of ENF equipment condition;

— record-keeping of scheduled and forced outages of the equipment, reliability analysis, record-keeping of failures;

— record-keeping of RPA operations;

— record-keeping of outage requests;

— logging and primary processing of load and voltage measurement data;

— real-time logging of changes in the networks with different voltages.

Electric network reliability analysis. Let us consider the task of collecting and processing information on forced outages and failures in the ENF networks, and equipment damage suffered by the consumer because of interruptions. This information is needed to prepare statistical characteristics of reliability and calculate the reliability indices of a network. The procedure for solving this problem is in many ways similar to the previous one and comprises four characteristic steps: compiling a special failure charts (FC), transmitting the gathered data to RPD CC and preparing the source information on the machine media (punching), running of routines to set data files, running of emergency analysis routines and output of machine (report) documents.

The reliability problem should fully utilize the data of the network condition logging subroutine residing in the machine to avoid redundancy. The emergency analysis system should be of the open-ended type, i.e. permitting extension or expansion.

Failure chart. The main source (primary) document is FC. FC contains data indicating the address of the damaged component (segment), the time of outage (year, month, date, hours, minutes), information on the damaged segment (the length of the network disconnected by the switch and the total power of transformers

disconnected by the switch); similar data for the segment disconnected by the trip (at fault localization). FC also specifies the faulty component (component name, equipment name and type, quantity, cause, nature of failure), type of outage (accident, unscheduled outage, failure of supply networks), duration of outage (fault localization, restoration), labour input for restoration, power underproduction, operation of relay protection and automatics.

The failure chart is an important document, filling-in and approval of which is a significant legal aspect vital for the technical-and-economic indices of the ENF operation. The filling-in and approval procedure should be set forth in special instructions.

Reliability analysis. After the FC data are inserted into the computer, the failure files are generated and checked, the reliability is analyzed according to a prepared algorithm. The failure analysis detects causes and evaluates remedies, qualifies the personnel. The statistical analysis and data processing make it possible to determine and refine the probability of equipment failure, more accurately estimate the required redundancy, calculate the reliability indices for different regions of ENFs and plan the repairs.

Output document forms. The reliability analysis output documents may be divided into three groups:

1. Reports on failure results: labour input for restoration, power underproduction, new equipment installed. All these data can be obtained for the desired time periods (year, quarter, month) and for the desired group of failures (e.g. failures of the lines fed from a given primary substation or of the particular voltage lines).

2. Data on failures of particular transmission lines for a given time period.

3. Report form approved by the Central Statistical Department.

The repair and reconstruction management tasks include:

— compilation of monthly, annual and long-term schedules for maintenance of transmission lines, substations and distribution networks, checks of RPA, oil sampling, etc.;

— drawing an estimate for repair of lines and substations;

— calculation of network schedules for carrying out repairs;

— calculation of balance-sheet cost of installations under construction;

— rating and accounting of repair operations;

— inventory of warehouses;

— record-keeping of employment of automotive transport, mechanisms, etc.

Substation MCS tasks. Substation MCS may be a segment of ENF MCS. Some problems of substation MCS are similar to those of ENF MCS. These include collection, processing, storage and display of information or transmission of it to a higher management level.

Besides, there are specific substation tasks which depend on the substation type.

The MCS tasks of unattended substations:

— voltage regulation with adaptive variations of the control law;

— selective (depending on the actual condition) disconnection of the distribution lines for frequency or voltage unloading in case of transformer or feeder overload with subsequent restoration of supply;

— selection of the optimal number of transformers to operate in parallel and control of their switching;

— tracing of a segment with decreased insulation in networks with an insulated neutral conductor;

— ranging of the damaged point;

— control of arc-suppression coils;

— control of communication channels.

Note that most of these tasks belong to real-time control.

The MCS tasks for large system super-high-voltage manned substations:

— display of information on the status of the substation circuits and operation variables;

— control of switchgear against the installation scheme displayed on the operator screen;

— programmed control of switching to decrease overvoltages;

— formulation of recommendations for the attending personnel for the case of emergency;

— checking of the present variables for correspondence to the preset values;

— transfer of some functions of the relay protection and automatic equipment to the computer.

Computerizing the protection functions increases the reliability owing to the use of special system diagnostic programs. It becomes possible to ensure the measuring device characteristics changeable according to a preset program, which is difficult to achieve in analog units; more sophisticated methods of constructing the relay protection may be developed since the computer offers massive amounts of information for analysing the system status (information on the pre-emergency condition, data from more sensors including those located at other installations). The computers provide for flexible automatic changing of the relay protection settings so that the system becomes adaptive. The experience of computerization of the relay protection in this country and abroad is not yet sufficient.

5

MATHEMATICAL MODELING IN POWER INDUSTRY

5.1. Production Process Variables

Controlled variables of production processes. Depict the installation to be controlled in the form of a "black box" (Fig. 5.1). Divide the operation variables into several categories and distinguish between the input variables and output variables. Next, divide the

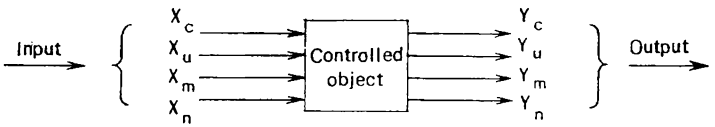

Fig. 5.1. System parameters

input and *output* variables into *controlled* (with subscript *c*) and *uncontrolled* * (with subscript *u*). The latter include the variables we cannot control (weather, power system load) or do not want to control, e.g. those negligible for the objective function. Besides, the process variables can be measurable (with subscript *m*) or non-measurable (with subscript *n*).

Rules for choosing controlled variables of production process. When constructing a mathematical model it is vital to properly select the controlled variables. The variables should be:

— representative, i.e. accurately characterize the production process;

— linked with the objective function; it is preferable that the objective function be measurable or at least computable by the indirect data of the measurable variables;

— highly sensitive and significant; the insignificant or low-sensitivity variables should be better transferred to the uncontrolled ones or to constraints;

— making up simple relationships which do not complicate the model;

— measurable (the non-measurable variables relate to external disturbances); they should be readily encoded and input to the ma-

* In the general case the control action can occur at the input or output of the system or both concurrently.

chine by the operators in the course of a routine activity, e.g. the data on the work performed can be loaded simultaneously with formalizing the request;

— linked with the fault location to simplify the diagnostics;

— characteristic of skill acquired by the operators in the course of work and the degree of their mastering.

The variables meeting all the above requirements are hard to choose, so that the operations research man has to be satisfied with, e.g., measurability and sensitivity of the variable and its simple relation to the objective function. It is a rule that the less clear is a phenomenon the more variables are needed to explain it.

5.2. Modeling Stages

Modeling. Modeling may be defined as a method of indirect cognition wherein the actual object (reality) is represented by a model capable of substituting the actual object at some stages of the cognition process.

Purpose of mathematical model. The mathematical models are used in MCSs for optimal control (as regards the objectives) of the production process, i.e. efficient decision making. This means that a certain mathematical entity representative of the actual object in some criteria is not only stored in the computer memory but is a convenient tool for controlling the production.

Construction of mathematical models. Assume it is necessary to construct a mathematical model of the existing enterprise and find out its control laws. The technological processes are diverse and their mathematical representation cannot be unified. For the modeling purposes the processes are divided into *typical subprocesses.* The greater is the number of the subprocesses the easier is to pick up the suitable typical scheme for the process. The general path of building a mathematical model of a technological process may be represented as an algorithm comprising six major steps (Fig. 5.2). Consider them in more detail.

Investigation of production process. The basis for investigating the production process is the experience gained in operation of the enterprise being automated or of a similar enterprise. The investigation includes observation, experiments, summarizing of previously gathered data. The experiments are carried out under the production or laboratory conditions. The successive approximation method is frequently used. An approximate description of the technological process and an approximate mathematical model are prepared on the basis of the investigation performed. The model calculation results are compared with the results of actual operation of the object. If the discrepancy is excessive, the model is improved. Such a method cannot always be employed in complex systems with

plurality of variables where the estimated conditions cannot be embodied because of great random walk of the parameters.

Detailed description makes a cornerstone for the subsequent steps. It is a description of combined properties of the technological pro-

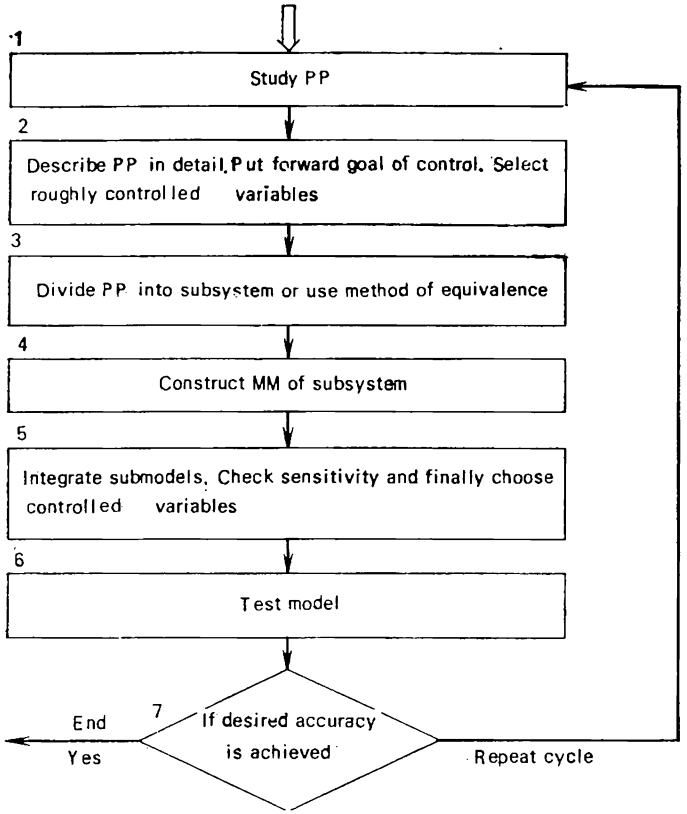

Fig. 5.2. Construction of mathematical model (MM) of production process (PP)

cess represented by simple relation or structural diagrams so that the objective is clearly defined. The detailed description sets forth and substantiates the objective function.

Breaking down of process into simple steps. This is aimed at simplifying modeling. Technical literature does not describe a representative set of typical mathematical models of typical technological processes in power industry, therefore the degree of breaking down is solved by the OR man independently using known typical examples. The simple step is a process element which can be described mathematically. It is good policy to use typical mathematical des-

criptions if available. The description should be simple and the variables should be selected as advised above.

The breaking down of the process is often substituted with equivalence.

5.3. Complete and Simplified Models

Representation of mathematical model. A model may be represented as a system of relations (equations) interrelating the parameters of the production process, input and output variables with other parameters and constraints. A complete mathematical model of any technological process comprises five groups of equations.

1. Equation of system effectiveness (objective function). It shows the degree of correspondence of a decision to the management objective. In the probabilistic form it may be written as

$$\mathscr{E}E\ (Y,\ X_c,\ X_u) \Rightarrow \max \tag{5.1}$$

where $\mathscr{E}$ is a symbol of mathematical expectation (dropped when the effectiveness equation is written in the deterministic form).

2. Coupling equation. It describes the technological process of the system and dependence of the output variables on other controlled state variables

$$Y = A\ (X_c,\ X_u) \text{ or } Y = A\ (X) \tag{5.2}$$

Such a relationship is sometimes called a *property* of an element or process. The property is a combination of relationships which makes the output variables Y dependent upon the input variables X. If signal $X\ (t)$ is fed to the input of an object and variable $Y\ (t)$ is obtained at its output, the property is operator A. It indicates the sequence and contents of operations for obtaining $Y\ (t)$ from given $X\ (t)$. Generally, operator A characterizes the input costs per unit output and advance (delay) of input with respect to output. The properties can be obtained theoretically with the use of special measurements or by direct identification (for determining the properties in the course of object functioning see Sec. 5.2). The properties can be written in the implicit form

$$A'\ (X,\ Y) = 0$$

which is often used for theoretical analysis of the object behaviour.

Stationary and non-stationary objects. If the object properties do not change in time, the object is considered stationary. However, ageing and other factors change the object properties so that most of the objects are non-stationary. The planning term for such objects is so selected that the object might be assumed stationary. This considerably complicates the mathematical modeling.

Assignment of coupling equations in computer memory. When modeling processes on a digital computer, the object properties are seldom assigned in the form of analytical relationships, more often as tables. It is convenient to represent the properties in the form of *approximating expressions*, e.g. interpolation polynomials. Such a writing is shorter. The precision of the process model is greatly dependent on the approximation. The polynomial parameters are usually chosen by the least-squares technique. This can be achieved in two ways: without imposing any constraints on the form of the curve obtained and imposing constraints, e.g. the requirements for convexity or monotonicity of the entire curve or absence of breaks at a certain preset segment of it. The approximation of the second type is more complex algorithmically and involves grosser errors, however, if the approximating expression is chosen successfully, the optimization of the model is drastically simplified. For instance, a model is considerably simplified if the properties are so approximated as to permit the use of the Lagrange optimization technique. If all the characteristics of the process are linear functions and the constraints are linear inequalities, the process can be optimized by the linear programming methods. Unfortunately the technological process characteristics are usually substantially non-linear.

3. Constraint equations. These equations show the permissible limits of fluctuation of the input and output variables of a system, the conditions of the technological processes. The constraints can be in the form of *equation* (the balance type constraints) and *inequality* (restrictions on the variable fluctuation limits). Generally a constraint can be written as

$$F_{con,\,i}\,(X,\ Y) \leqslant A_{con,\,i} \tag{5.3}$$

As regards function F_{con} the constraints can be linear or nonlinear. They can be written in the *deterministic* (descriptive) or *stochastic* (probabilistic) form. The constraints are often represented as a permissible range of variables. For instance, the constraints for the input (controlled) variables in the deterministic form can be written

$$X_{i,\,c,\,\min} \leqslant X_{i,\,c} \leqslant X_{i,\,c,\,\max} \tag{5.4}$$

Probabilistic constraints are written as a certain minimum permissible value p_0 being a threshold probability of satisfying the permissible limits of the variable. A constraint for the controlled variable is as follows

$$p_i\,(X_{i,\,c,\,\min} \leqslant X_{i,\,c} \leqslant X_{i,\,c,\,\max}) \geqslant p_{0,\,i};\ \forall i \in I_{in} \tag{5.5}$$

This means that the controlled variable $X_{i,\,c}$ is inside the permissible range to a probability p_i greater than (or equal to) the threshold

probability $p_{0,i}$ for all the values of it belonging to a permissible set I_{in}.

The constraints can be *unilateral* ($X_{i,c} \leqslant X_{i,\max}$) and *bilateral* (all the above constraints are bilateral). They can be stringent, i.e. do not allow any violations in order not to destroy the installation or conflict the physical sense (resource constraints), or flexible. Violation of the latter causes additional damage but does not lead to accidents.

The *constraints for the organizational systems* may be not technological but directive (e.g. working schedule); such constraints have a strength of the law and are mandatory to satisfy. The constraints may comprise socio-labour restrictions, e.g. shift duration limits, etc.

A suitable writing of the effectiveness equation automatically accounts for a number of constraints with the aid of penalties. If E is criterion, the constraints can be allowed for by writing it as

$$\widetilde{E} = E + \Sigma\ (X_i - X_{i,\max})^n Pe_0 \tag{5.6}$$

where $\widetilde{E}$ is a new objective criterion; Pe_0 is a penalty coefficient; $n \geqslant 2k$ is a positive integer; $X_{i,\max}$ is a nominal (permissible) value of the parameter i for which the constraints are to be taken into account, and

$$Pe = \begin{cases} 0, & \text{if } X_i \leqslant X_{i,\max} \\ Pe_0 (X_i - X_{i,\max})^n & \text{in all other cases} \end{cases} \tag{5.7}$$

Such a technique is applicable only to flexible constraints. It is preferable that the penalty coefficient correspond to the actual cost of losses inflicted by the violation of the constraint. However, determination of its numeric value involves great methodological problems therefore Pe_0 is often assumed sufficiently great.

4. Optimal control (optimization) equations. These equations are the principal result of optimization. The control equation is a function representing an optimal relation between the controlled variables of the system and the objective, output, and uncontrolled variables

$$X_{c,0} = f_c\ (E,\ Y,\ X_{un}) \tag{5.8}$$

The search of the control law is the final stage of system optimization. It is effected with the use of the optimization technique.

5. Adaptation equation. MCS is substantially an adaptive system. Meant by adaptation is the process of changes of the parameters, structure and control actions in the system on the basis of the current information with a view to achieving a particular, usually optimal, status of the system with the initially indeterminate and varying operating conditions. The control process should be so organized as to use to the advantage the available information on the optimal decisions made during operation of MCS and, if the situation changes,

to change the variables and management structure so as to maximize the effectiveness. In the explicit form it may be written as minimizing the discrepancy between the observed economic conditions of the system operation and the present conditions

$$E_0 (X, Y) - E (X_1, Y_1) \Rightarrow \min \tag{5.9}$$

where E_0 is the maximum effectiveness achieved under the conditions approximating the present external ones.

As applied to our case, the adaptation implies the best rearrangement of the interrelated system of control algorithms to suit the existing operating conditions of the controlled object. When used with a power installation, the adaptive system accounts for changes of its characteristic and objectives. Note that the adaptation presupposes a mandatory memory to store the previous successful results of decision-making.

A complete mathematical model of the production process comprises five groups of equations (inequalities) outlined above. The absence of one or several groups of equations determines the degree of model simplification. Consider some simplified models.

Simulation model. Apart from the complete models, simplified mathematical models are frequently used. They comprise only some of the five equations discussed above. For instance, the models which do not include the adaptation equation define the nonadaptive system class.

Among them is a simulation model which has found wide application. It does not include the control and adaptation equations and is intended to allow the operator to evaluate the system behaviour by reference to the set of external factors or controlled variables. The simulation model contains the coupling and constraint equations and involves calculation (not optimization) of the objective function, i.e. the model does not include the optimization segment. The optimization model is necessarily built with the optimal control equations and after its implementation, the computer outputs a set of controlled variables. The inclusion of the optimization equations often requires simplifying the coupling and constraint equations therefore the simulation models may be far more precise. The simulation models are widely used in the interactive computer systems. The search of the optimal control variant with the aid of such models is more complicated and is greatly dependent on the skill of the operator.

Operating condition models. The object control problem is sometimes confined to satisfaction of the constraints. If the constraints are numerous, it is a difficult task to bring a unit to the permissible operating limits and maintain its normal functioning. The objective function in modeling of such a process is the constraints. The con-

ditions are brought into the permissible range by minimizing the total square deviation of the variable beyond the specified limits.

Cognition model. The simplest model of an object is the model comprising only the characteristic of the latter. Such a model is not suited for decision making but can be used to study the phenomenon.

5.4. Example Model

Construct a mathematical model for the power system comprising n thermal power plants operating in parallel. The loss of energy in the electric networks may be neglected.

Coupling equation. To obtain the coupling equation, regard each power plant as a black box (Fig. 5.3). Fuel in the amount B_i, t/h,

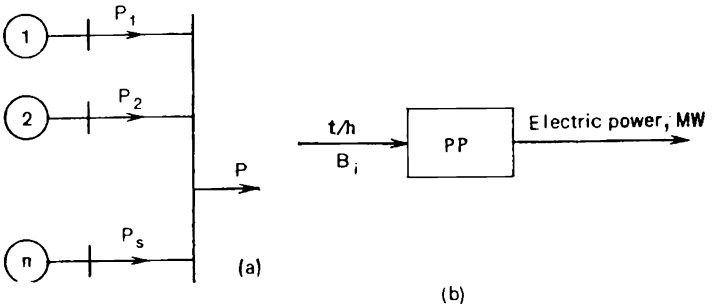

Fig. 5.3. To power system modeling
(*a*) simple system diagram; (*b*) "black box" representation of power plant

is fed to the input of the black box and power P_i, MW, is obtained at the output. Assume power P_i be a controlled variable. Then the coupling equation is the relationship between the fuel consumption and power B_i (P_i). These characteristics are considered known, they are derived from special tests performed at the power plant.

Constraints. Two constraints are to be satisfied: (a) the equation type: the total power of all the plants should be equal to the given load power P at a given moment of time; (b) the inequality type: for the variation range of the controlled variable, in our case for the power limits of the plants

$$\text{(a) } \Sigma P_i - P = 0; \text{ (b) } P_{i,\,\min} \leqslant P_i \leqslant P_{i,\,\max}; \quad \forall i \in n$$

Objective function. The objective function will be the cost function, e.g. the cost of fuel consumed. This condition approximates to the maximum profitableness of the system

$$E = \sum_{i=1}^{n} c_i B_i (P_i) \Rightarrow \min$$

where c_i is the cost of one ton of fuel.

Control equation. To obtain it, solve the problem of minimizing the objective function. Using the Lagrange method, search the minmum of a certain value Φ:

$$\Phi = \sum_{i=1}^{n} c_i B_i (P_i) + \lambda \left(\sum_{i=1}^{n} P_i - P \right) \Rightarrow \min$$

where $\lambda \geqslant 0$ is the Lagrange multiplier. If the balance equations are satisfied, the minimum of Φ coincides with the minimum of the objective function. Find the minimum of Φ from the conditions:

$$\frac{\partial \Phi}{\partial P_i} = 0, \quad \forall i \in n$$

In the general form the control equation may be written (see Section 6.3) as

$$c_i \frac{\partial B_i (P_i)}{\partial P_i} = \text{idem}$$

The symbol on the right side implies that the condition for all the plants is the same. By using the Lagrange method we restricted the type of the coupling characteristics $B_i (P_i)$ by default: the curves should be convex downward for applying the method.

Adaptation equations. These are hard to be expressed quantitatively. It may be assumed that under normal conditions the control is effected according to the derived law minimizing fuel consumption. In a more complex situation when an outage occurs at one or several plants, the adaptive device must change the objective function to transfer from the maximum economy control to the maximum reliability or survivability regulation. This will necessitate rearrangement of the control algorithm. The adaptation methods can be also used for calculating the characteristics $B_i (P_i)$.

Simulation model. The simulation model for this example is a set including coupling, constraint equations and the equations for calculating (not optimizing) the objective function, i.e.

1. $B_i (P_i)$; $\forall\, i \in n$
2. $\sum_{i=1}^{n} P_i - P = 0$
3. $P_{i,\,\min} \leqslant P_i \leqslant P_{i,\,\max}$; $\forall i \in n$
4. $E = \sum_{i=1}^{n} c_i B_i (P_i)$

Assigning a set of powers of any $(i - 1)$ plants which meet condition 3, find the power of the last plant from condition 2. If it is permissible (i.e. satisfies condition 3), calculate E and estimate its value. The simulation model comprises $n + 2$ equations and $n + 1$ constraints.

Operation model. This model includes three groups of equations. The objective function coincides with the constraints and takes, e.g. the following form: minimization of the penalty function when the controlled variable deviates from the permissible value

$$E = \Sigma\, Pe_{0,i}\,(P - P_p)^n$$

By using this objective function with the object characteristics, find the appropriate control equation.

The *cognition model* will include only the characteristics of the units.

5.5. Peculiarities of Model Construction

Three types of models. The model is greatly dependent on the information available, its validity, method of obtaining and the optimization technique used. Discuss three cases, when:

(a) it is possible to model the situation and obtain the solution for the optimal behaviour of the system; this is the case of the optimization model and the decision making can be fully entrusted to the machine;

(b) it is possible to model the situation but no solution will be given by the machine (simulation model); the decision is made by the man;

(c) the situation cannot be modeled on the whole for lack of information, means or knowledge; good policy in this case is to break down the problem into subproblems and try to build the simulation models for each of them.

Case (a) belongs to the sphere of routine calculations, cases (b) and (c) to the sphere of the man-machine systems. The experience gained in the operation of MCSs reveals that as the information is accumulated, the amount of routine calculations increases, while those of cases (b) and (c) decrease. That seemed yesterday impossible to formalize is successfully computerized today.

Model simplicity. Though simplification of the model impairs its precision, it is quite mandatory on most occasions. The mathematical model is a reasonable compromise between the simplicity and precision.

Model system. To describe a behaviour of even one object under different conditions or to solve various production problems a certain set of models is needed.

Deterministic and probabilistic models. There may be three cases of model construction: *deterministic* when all the information is given in the exact quantities (deterministic model); *probabilistic-deterministic* when the links include probabilistic (random) values but a probabilistic description is known for each of them; *indeter-*

minate when a probabilistic description is not known for one of several stochastic values and it is assigned by its variation range.

If at least one equation is written in the probabilistic form, the entire model is probabilistic (stochastic) and relates to the second or third group. When building mathematical models for power industry, probabilities of events have to be often taken into account. In the probabilistic-deterministic model the stochastic values are assigned by the distribution law. They are frequently restricted to the numerical characteristics, e.g. mean values, root-mean-square deviations (variances) and correlation aspects for several random values. For the probabilistic-deterministic model, the solution depends on the particular magnitudes assumed by the random variables. The single-valued variant is obtained only as optimal in the mean (as a minimum of mathematical expectation of the objective functional). Optimization of such problems is labour consuming. Statistic modeling methods are often used.

In case of uncertainty, it can only be said of selecting some rational variants. The uncertainty of the raw data causes the uncertainty of the final decision made volitionally among the variants, each rational in some respects. A number of criteria game theory, e.g. the minimax theorems, can be used for the purpose. The most promising trend is to accumulate observations in the course of operation and to transfer control from the uncertainty conditions to the conditions of probabilistic-deterministic models.

Accounting of disturbances (environmental) in mathematical model. The disturbances can be internal and external. The internal disturbances are linked with the condition of the technological equipment and changes in the production conditions (ambient temperature, cooling water temperature at thermal power stations, etc.), the external ones with the delivery of raw materials, energy, demand fluctuations. All these disturbances, except for the scheduled or directive ones, are stochastic. If the disturbance distribution law is known, it can be superimposed on the mathematical model of the object to study the disturbance impact by, e.g., the Monte Carlo method. The systems with continuous-run production can be described on most occasions as deterministic processes.

5.6. Modeling of Continuous Production Processes

Representation of continuous production. A continuous production is a combination of technological installations and apparatus interconnected by product conduits (pipelines), electric networks, etc. A model of such a production can be represented in the form of a graph. Its nodes are the technological apparatus or interconnections of several pipelines or transmission lines, branches are the pipelines or other technological flows. The structure of such a production can

be stored in the digital computer in the form of two arrays: branches and nodes. Each branch is written by its beginning and end, i.e. the number of the node it emerges from and the number of the node it enters, and by its labels. The node array is a combination of numbers and sets of parameters descriptive of a given technological node (load, maximum capacity, pressure, temperature, etc.).

Control of continuous production. The control methods are dependent on the particulars of the technological process. If the process is steady and flows under the conditions approximating optimal, control may be confined to maintaining (stabilizing) the preset conditions. This is the simplest method of control rarely encountered in power industry where considerable sluggishness of the equipment must be taken into account. For instance, it is impossible or unfeasible to shut down some units, while stoppage of the others results in cooling of the equipment and re-starting it would require great amounts of fuel and prolonged time. On the other hand, reduction of the enterprise load may lead to unprofitable or nonsteady operation of the equipment and necessitate disengagement of some of the parallel units which, however, are to be rapidly committed as the load increases. The continuous productions involve a specific problem of the expedient number of normally operating units (unit selection problem).

Description of continuous production by the Kirchhoff law. Continuous production systems can be frequently described as determinate systems, they are modeled with the aid of the balance equations or the Kirchhoff equations. Most frequently is used the first Kirchhoff equation postulating that the sum of material flows converging in a node having a zero capacity is equal to zero. Consider the formulation of the balance equation for the system node.

Balance equations for a node. If $x_{i,s}$ is the input variable at the sth moment of time, $y_{i,s}$ is the output variable at the sth moment of time, then the balance equation can be written

$$\sum^{k} x_{i,s} = \sum^{l} y_{i,s} \tag{5.10}$$

where k and l are the number of inputs and outputs of the system, respectively. Such a writing holds good for a system without transportation lag (without buffer vessel). The advent of the *intermediate* (buffer) *vessel* changes the input-output coupling equation

$$\frac{dv_i}{dt} = \sum_{s=1}^{k} x_{i,s}(t) - \sum_{s=1}^{l} y_{i,s}(t)$$

where v is the capacity of the product inventory.

After integration, this equation becomes

$$v(t) = v_0 + \int_{t}^{t_0+t} [\Sigma x_{i,\,s}(t) - \Sigma y_{i,\,s}(t)]\, dt$$

This equation is called the *main inventory equation.*

Accounting of buffer vessel in modeling. If the inventory is sufficient and $\frac{dv}{dt} \to 0$, the system input and output can be considered independently of each other. This means that control of continuous processes is greatly dependent upon the buffer vessels available in the technological flow. If these vessels (warehouses) have a sufficient capacity, the process occurring between them can be modeled and optimized separately. The finished product warehouse at the end of the continuous process allows one to stabilize the production in case of fluctuating demand. The electric power systems have no finished product warehouses so they cannot be divided into independent subsystems.

5.7. Adaptive Models

The *adaptive models* are the models which are modified as the information on the object is accumulated. The adaptive models are extensively used for controlling continuous processes. At the beginning of operation the model parameters (operator A, see Sec. 5.3) are determined on the basis of the available information. The optimal control actions are determined by this model. The control actions are implemented to obtain new experimental data on the system behaviour which are used for new improvement of the model. The new model is utilized to refine the control actions; then the latter are again implemented and the model is improved anew and so on. If the model parameter calculation process converges, such a control leads to optimal results.

Object identification. Each step of such a process involves determination of the object characteristics, i.e. identification of the object. Meant by identification is finding out the degree and form of the interrelation between the input and output variables (finding operator A or object characteristic), the stationarity of the said functions and similarity between the model and the object.

Let us divide the adaptation methods into two groups: for stationary and non-stationary objects. The second group is reduced to the first at the stationarity intervals. The identification is effected by various modifications of the least-square method and the stochastic approximation technique.

Least-square method. Consider an object with k inputs x and one output y. Let the relation between the variables be described by the equation

$$y = \Sigma a_i \varphi_i (x) \tag{5.11}$$

or in the matrix form

$$\mathbf{y} = \mathbf{a}^t \boldsymbol{\varphi} (x) \tag{5.12}$$

where $\varphi_i (x)$ is the assigned approximating function; $\mathbf{a}^t$ and $\mathbf{y}$ are the n-dimensional column vectors; superscript t stands for transposition.

The problem of identification of a stationary object is confined to the search of the best estimation of vector $\mathbf{a}$. The $\mathbf{a}$ vector is estimated for the minimum mean-square error of the object characteristic representation at m successive time intervals ($j = 1, 2, \ldots, m$). The representation error square θ

$$\theta (\mathbf{a}) = \left(\frac{1}{m} \sum_{j=1}^{m} \mathbf{y}_j - \sum_{i=1}^{k} \mathbf{a}_i \varphi_i (x_j) \right)^2 \Rightarrow \min \tag{5.13}$$

After equating to zero the partial derivatives of θ with respect to the coordinates of vector $\mathbf{a}_i$, we obtain a system of linear equations

$$\left.\begin{aligned}
\sum_{i=1}^{k} \mathbf{a}_i \sum_{j=1}^{m} \varphi_1 (x_j) \varphi_i (x_j) &= \sum_{j=1}^{m} \mathbf{y}_j \varphi_1 (x_j) \\
\sum_{i=1}^{k} \mathbf{a}_i \sum_{j=1}^{m} \varphi_s (x_j) \varphi_i (x_j) &= \sum_{j=1}^{m} \mathbf{y}_j \varphi_s (x_j) \\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots & \\
\sum_{i=1}^{k} \mathbf{a}_i \sum_{j=1}^{m} \varphi_m (x_j) \varphi_i (x_j) &= \sum_{j=1}^{m} \mathbf{y}_j \varphi_m (x_j)
\end{aligned}\right\} \tag{5.14}$$

or in the matrix form

$$\mathbf{W} (a)\, \mathbf{a} (t) = \mathbf{U} (t)$$

Hence the estimation vector

$$\mathbf{a} (t) = \mathbf{U} (t)\, \mathbf{W}^{-1} (a) \tag{5.15}$$

where

$$\mathbf{W} (a) = \sum_{j=1}^{m} \varphi_s (x_j) \varphi_i (x_j)$$

$$\mathbf{U} (t) = \sum_{j=1}^{m} \mathbf{y}_j \varphi_i (x_j)$$

The estimation vector $\mathbf{a}(t)$ can be calculated if the matrix determinant W is other than zero, i.e. if the sequence of observations comprises n linearly independent vectors. For more detail on the identification technique, refer to Sec. 7.9.

5.8. Design Models

Designing of a system is adaptation of the available means for performing particular functions or coordination of components and isolated actions for obtaining the desired results. Designing requires a compromise that would ensure a reasonable (sometimes optimal) equilibrium between the system objectives and means available. The system design problem may be represented as a process of minimizing the mathematical expectation $\mathscr{E}$ of a certain effectiveness index E which depends on a set of installation parameters $\mathbf{X}_1$, operating conditions $\mathbf{X}_2$, time t, and the system reliability θ:

$$\mathscr{E}\{E[\mathbf{X}_1, \mathbf{X}_2, t, \theta(\mathbf{X}_1, \mathbf{X}_2, t)]\} \Rightarrow \min, \quad \mathbf{X}_1 \in \tilde{\mathbf{X}}_1; \mathbf{X}_2 \in \tilde{\mathbf{X}}_2 \tag{5.16}$$

The vectors $\mathbf{X}_1$ and $\mathbf{X}_2$ belong to a certain permissible set $\tilde{\mathbf{X}}_1$ and $\tilde{\mathbf{X}}_2$ (constraints), while the reliability depends on the system parameters, operating conditions and time.

MCS synthesis and analysis problems. Meant by the automated control system is the unity of the controlled object and the control system. This is often forgotten and the management information segment is considered as MCS separately from the controlled object. If MCSs are created as a superstructure of the existing objects, such an approach may have a serious detrimental effect; new enterprises should be constructed concurrently with MCSs.

Synthesis stage. A complex management control system based on parallel designing of the controlled object and management information system may ensure such a high effectiveness which cannot be achieved by a mere superstructure. The integration of the object and the control system will result in a more versatile control, decreased strength and other technological margins of the equipment. The centralized direct supervision of the equipment condition, reduced probability of variable deviation beyond the critical limits, alongside with the efficient machine control in emergency make it possible to substantially cut the equipment cost and improve its performance. The today's stage of MCS may be regarded as the stage of analysis of the existing objects. The tomorrow's stage will be the stage of synthesis, i.e. concurrent designing of the controlled object and MCS.

Synthesis designing is a combined designing of the object and its control system. After the objectives of the technological process are

formulated, it is divided into subsystems. The objectives are determined and the control system is chosen for each subsystem. The subsystems are combined into a single hierarchical control system. It spans three levels of the operation control situational hierarchy:

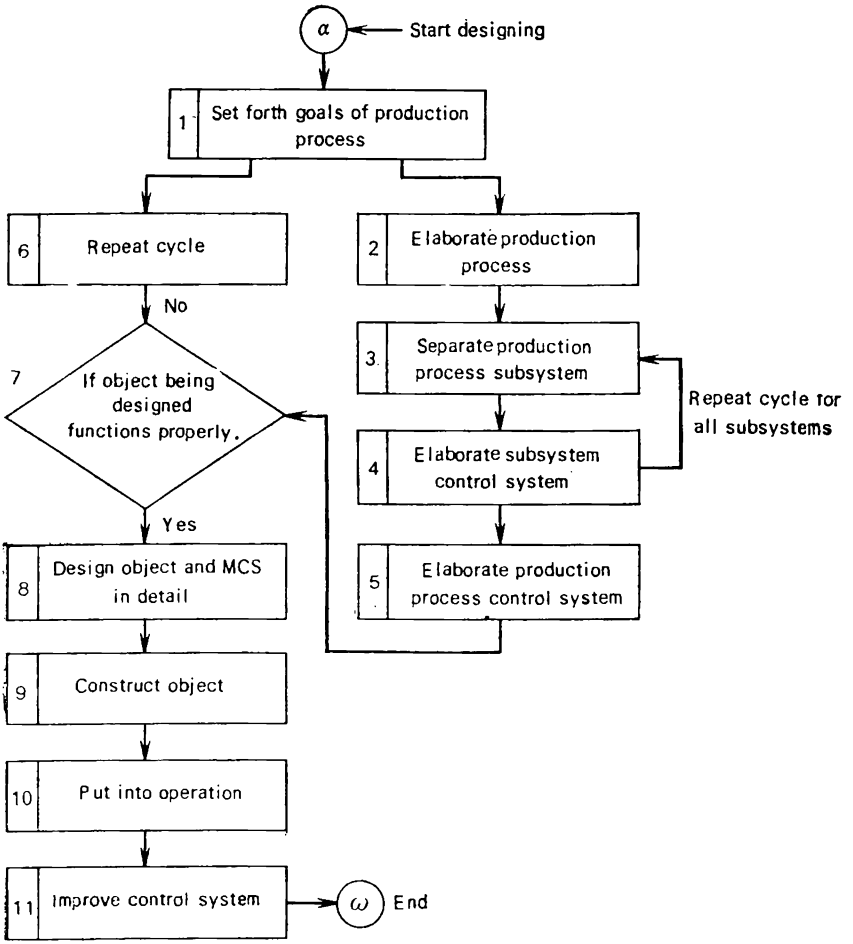

Fig. 5.4. Use of models in designing production system with integrated MCS

emergency, normal (permissible) and optimal control. Besides, a spatial hierarchy is established for the divisional subsystems (working bays). The quality of functioning of the entire enterprise is checked and, if proved unsatisfactory, the division into the subsystems is modified with refining the parameters of the control system. The other stages of creation of an object are sufficiently evident (Fig. 5.4).

The object created as outlined above cannot function without an MCS and if the latter fails the operator will not be able to fully replace the computer. This means that MCS designed on the synthesis principle should meet more stringent reliability requirements than superstructure MCSs.

Adaptation of equipment to MCS. Power generating equipment was developed long ago and is hardly suitable for cybernetization. Many units have not yet been provided with the requisite instrumentation. The control per se is overcomplicated and is carried out from many stations. Systems approach and integration of the control system and the technological process allow one to more accurately define the requirements for control of the particular subsystem, its instrumentation. The mathematical models in power industry should be constructed with due regard for the multiple performance criteria and hierarchical structure of the control systems.

5.9. Accounting for Multiple Performance Criteria

In practice, decision-making is based on several substantial optimality criteria all of which are to be taken into account. This evolves the problem of multiple criteria called *vector optimization.* To solve this problem, the criteria conflict should be accounted for and compromised. Unfortunately theory of vector optimization is far from completion so that we can review only the simplest results.

Let $\mathbf{X}_0$ be selected from a permissible set of solutions D. Its quality is estimated by a set of n scalar criteria $c_1, c_2, \ldots, c_n$ comprising the effectiveness vector $\mathbf{E}$. The vector $\mathbf{E}$ is linked with the solution by a certain mapping $\mathbf{X}_0 \rightarrow \mathbf{E} = \mathbf{F}(x)$. It is necessary to find such a permissible and best solution $\mathbf{X}_0 \in D$, which would optimize the effectiveness vector $\mathbf{E}$. The optimization model is

$$\mathbf{X}_0 = \mathbf{F}^{-1} [\text{opt } \mathbf{E}(\mathbf{X})], \quad \mathbf{X}_0 \in \mathbf{D} \tag{5.17}$$

where opt is the optimization operator; $\mathbf{F}^{-1}$ is the inversion of $\mathbf{E}$ to $\mathbf{X}_0$.

Vector optimization. The problem of choosing the optimality principle resides in how the optimality of the solution obtained is to be interpreted. If the optimization is scalar (single-criterion), the principle of selecting the optimal solutions is explicit, e.g. $\mathbf{E}(\mathbf{X}_0) \geqslant \mathbf{E}(\mathbf{X})$ if the criterion is maximized. In case of vector optimization, the principle of optimal decision-making should be determined. This problem is called *scalar problem* and resides in the selection of a certain generalized scalar criterion being a function of local criteria. The principle (concept) is chosen by the operator.

Trade-off range. Distinguish a certain range $R \in D$ in the range of permissible solutions D. Let R be such that all its solutions cannot be improved simultaneously with respect to all local criteria.

Thus any solution from R contradicts at least one local criterion. Name range R the trade-off range. When selecting any solution from this range, a trade-off is mandatory. In vector optimization the solution is always selected from R since beyond this range the solution can be improved with respect to all the criteria simultaneously. Therefore, the first step in vector optimization is to find the boundaries of the trade-off range, which narrows the range of the possible solutions. Further optimization involves invasion into the trade-off range.

Trade-off principles. Consider some of the trade-off principles. Start with the *true trade-off*. Let all the criteria have equal significance. The trade-off is true when the deterioration of one or several criteria does not cause the relative improvement of other criteria. The discounted cost is introduced

$$\varkappa_i = \frac{1}{c_i} \frac{\mathrm{d}c_i(X)}{\mathrm{d}X} \tag{5.18}$$

and such a solution is chosen that the discounts are equal for all the local criteria

$$\varkappa = \text{idem} \tag{5.19}$$

The true trade-off principle is an equivalent of the principle of maximizing product II of all the criteria

$$X_0 = F^{-1}\left(\max \prod_i (c_i(X_i))\right), \quad X \in R \tag{5.20}$$

This is equal to maximizing the sums of the criteria logarithms

$$X_0 = F^{-1}\left(\max \sum_{i=1}^{n} \log c_i(X_i)\right), \quad X \in R \tag{5.21}$$

If the criteria are of the different significance, an additional coefficient a can be introduced at the discounted cost, assuming

$$\varkappa_i = a_i \varkappa_i$$

to maximize the equation

$$X_0 = F^{-1}\left(\max \prod_i c_i^{a_i}(X)\right), \quad X \in R \tag{5.22}$$

Properly correcting the discounted cost is very important though difficult.

Normalizing criteria. The true trade-off principle does not depend on the criteria scales. This, as well as the physical clarity of the approach, constitutes the major advantages of the principle. Unfortunately it is not universal so that other optimization techniques have to be frequently used. They require normalizing, i.e. scaling, of the criteria. For instance, the absolute value of a criterion may be

substituted by its relative value, e.g. with respect to the maximum possible value of the local criterion

$$\tilde{c}(X)=\frac{c_i(X)}{\max \tilde{c}_i(X)}, \quad X \in R \tag{5.23}$$

When the true trade-off principle is used for the normalized values, the criterion with the maximum local optimum is the obvious choice. However, the criteria equilibrium is disturbed in this case which is a shortcoming of such a normalization. There are other normalization methods which also suffer from shortcomings.

Integral optimization principle. The general case is the mean-integral optimization

$$X_0 = F^{-1}\left(\max \sum_i \tilde{c}_i^s(X)\right), \quad X \in R \tag{5.24}$$

Here the optimality criterion is the mean to the power s of the normalized c_i sum.

Consider two extreme principles of optimality that may be derived from the integral principle by appropriately selecting s.

The *Tchebyshev uniform optimization* requires a uniform increase in the level of all the normalized criteria with the minimum ones being the first to increase

$$X_0 = F^{-1}(\max \min \tilde{c}_i(X)), \quad X \in R \tag{5.25}$$

Differential optimization is contrary to the Tchebyshev technique and involves first of all maximization of the maximum local criteria

$$X_0 = F^{-1}(\max \max \tilde{c}_i(X)), \quad X \in R \tag{5.26}$$

This criterion has a limited sphere of application but is convenient for the synthesis and analysis of the bottlenecks.

Accounting for criterion priority. The last three of the above-mentioned principles postulate that all the normalized criteria are of equal significance. The criterion significance can be taken into account by multiplying the weighted criterion by its cost a_1, i.e. by additionally normalizing the criterion with the cost vector.

Practical methods of accounting for multiple criteria. In the light of the theory outlined above, consider several practical methods of vector optimization. They are, however, a possible approach rather than an actual universal tool.

Rigid priority principle. Arrange the criteria in a row according to their significance taking into account that c_1 is preferred to c_2, c_2 to c_3 and so on. Find the local optimum of the most significant criterion c_1. Fix it as a constraint and find the local optimum of the second criterion, again fix it as a constraint, etc. The feasible area will gradually decrease. Such an approach is effective only when the

"area rather than point" criterion is used at each stage (a certain area of solutions approximating optimum is searched rather than one local point of extremum). As a result of successive reduction of the area by accounting for each successive criterion, we obtain a fairly narrow quazi-optimal subset of solutions. The final solution will be chosen by the man.

Suboptimization. The criteria are ranked according to importance, the most significant is chosen and the others are transferred to constraints. This technique originates from the rigid priority principle and is used fairly often.

Mean-weighted criterion. Different criteria can be weighted, e.g. by expert opinion, to generate a mean-weighted criterion

$$E = a_1c_1 + a_2c_2 + \ldots + a_nc_n \tag{5.27}$$

where $a_i \geqslant 0$ is the weight of the ith criterion. The control decisions are made according to the extremum of said weighted criterion.

Expert selection of final decision. Let us optimize the system n times for each of the criteria. Compare the results and select one of them by the expert opinion method. The disadvantages of this method are in the prolonged time required, probable incompatibility of the solutions when the constraints are satisfied, and a certain voluntarism in making the decision. If none of the above methods of criterion selection have proved satisfactory, it is good policy to estimate them from the viewpoint of a higher level of the control hierarchy.

5.10. Accounting for Control Hierarchy in Modeling

The power industry is controlled on a hierarchical principle. Hierarchy implies several control stages and subordination of the lower level to the upper one.

Distinguish between three aspects of the hierarchical control systems: a successive vertical arrangement of subsystems; a priority of the upper level subsystems over the lower level ones; dependence of the upper level activity on the execution of functions by the lower levels.

Need for hierarchy. The hierarchical structure is necessary since the controlled system is too great to be coped with directly because of excessive amounts of information. The need for hierarchy may be interpreted so that the capacity of the object language surpasses that of the observer's and it is impossible to express all the components of the object simultaneously in the observer's language. On the other hand, the control hierarchy represents the physical hierarchy of the large systems (including economy) composed of sufficiently independent levels.

Advantages. The hierarchical control offers a number of advantages. When creating industrial and administrative mergers, the sub-

ordinate and existing segments are hard to rationalize. The control system frequently develops by adding some elements of a higher level. It means that the hierarchical structure allows integrating the control system. In such systems, the functions are positively divided among the control stages, subordination of the lower segments to the upper ones is mandatory, and no functions are duplicated. If the control structure is sophisticatedly constructed and the lower levels are reasonably independent in making decisions, the available resources are utilized more effectively. The hierarchy simplifies modeling of the complex actual systems; it allows dividing intricate problems into subproblems and solving them with a limited capabilities of each level, facilitates programming of MCS functions. In conclusion it increases the adaptation and survivability of the system. External disturbances and faults are often localized only at the lower levels with a substantial assistance rendered by the higher segments for normalizing the situation. The control hierarchy in the USSR is based on the democratic centralism principle.

Drawbacks. The behaviour of the hierarchical systems is very complex and difficult to control. The system functioning is hard to analyze or act upon from without. Besides, the control levels may conflict with each other.

Problems of transmitting messages along the hierarchical chain. When transmitting a message (order, information) and waiting for the report on execution, the manager risks to be misunderstood. This may occur if the addressee founds the message non-clear (e.g. excessively long). If the message is too flat and involves no attempt for establishing a psychological contact with the subordinate, it may be met negatively or even with animosity. It may arrive at a wrong moment or under unfavourable conditions (e.g. noise during transmission of oral messages). The probability of obtaining wrong messages increases with the number of the hierarchical levels.

Decentralization of control. As the size of the enterprise increases, the manager becomes unable to make all the decisions on his own. He transfers some of his powers to the subordinate or specially organized administrative subunits. If the part of the transferred powers is considerable, the control is called decentralized. A search of the reasonable degree of decentralization is vital for MCSs. The measure of decentralization can be the number of decisions made at the lower control levels as a percentage of the total number of decisions.

Decentralization proves effective at large enterprises where the centralized control would require a plurality of stages. It is also effective at subunits (branches) situated far away from the main production. Sometimes decentralization obstructs pursuing the same policy, impedes supervising the management. It requires well-trained managers since a rule-of-thumb manager will take a wrong decision contradicting the general interests or will be afraid

to make any decision at all. The foreign literature highlights the advantages and drawbacks of centralized and decentralized control systems. When solving this problem for creating an MCS, it should be borne in mind that the search of the reasonable decentralization is primarily the search of the sophisticated measure. The chosen decentralization should be best suited for given conditions.

Impact of hierarchical level on dynamics of control and information flows. The higher is the control level, the larger is the area encompassed by the real-time control. As moving upward, information more and more lags behind the technological process. The management functions become more generalized, the control dynamics decreases, the decision-making operations require more time. The computers of the lower levels operate real-time in pace with the technological process*. The information flows are averaged as they are conveyed to higher levels. The amount of information put out from a unit for an upper level is compressed as compared with that put into the unit from a lower level. The units may be regarded as data-use points when the information moves from bottom to top. On the contrary when the directives are transmitted from the higher level to the lower one, the units generate additional information.

On requisite number of hierarchical levels. A reasonable number of hierarchical control levels varies with the size of production, number of subunits, nature of data processing at the units, distance between the subunits and communication channel cost. To find the number of levels, it is possible to use the following estimation. Let m_s be the number of the control subunits; k_{com} be the data compression coefficient at the control unit, then the requisite number of control stages is

$$n_c = \frac{\log m_s}{\log k_{com}} + 1 \qquad (5.28)$$

This formula is derived for an average loading of management, equal compression coefficient for all the levels, and the number of processing operations proportional to the amount of information. The number of the levels depends on the degree of data processing (compression coefficient k_{com}). If $k_{com} = 3.2$, then with $m_s = 10$, $n_c = 3$, with $m_s = 100$, $n_c = 5$. If $k_{com} = 10$, these figures become 2 and 3, respectively. The maximum possible number of levels is not too great so that a reasonable n_c can be found by the exhaustive search. The designers of MCSs usually strive for minimizing the hierarchical levels.

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* In a sense, a lower level is more difficult to control.

5.11. Fundamentals of Hierarchical System Theory

Three types of hierarchy. As general theory of hierarchical systems is very much in its infancy, we shall brief below only some of its postulates.

Three types of hierarchy of continuous production MCSs can be distinguished: spatial, temporal and situational. The spatial hierarchy relates to systems the installations of which are spread over vast territories. The vaster is the territory of the control area, the higher is the control level. The temporal hierarchy stems from the need for differentiating the time periods of control (scaling) from very short (e.g. 15 min in the real-time control) to longer periods (e.g. in daily planning—hours and shifts, weekly—days, monthly—weeks or days, quarterly—months or seldom ten-day periods, yearly—quarters and months). The longer is the time interval, the higher is the control level. The situational hierarchy relates to the operating condition of the enterprise (installation). The highest level of this hierarchy relates to emergencies, the lowest one, to normal operation. The intermediate level is the post-emergency control, when the installation is brought back to normal duty.

Direct links. As the information moves along the hierarchical structure, each segment modifies, supplements, details or compresses the message. With the great number of levels, the signal movement is retarded and the probability of errors increases. To speed up the control, the elements of one hierarchical level should be enabled to establish direct production relations by providing information channels (links) in between. No links are allowed between the elements of different levels, otherwise the autocracy of management is infringed.

Strata, layers, echelons. Different hierarchical systems have different applications. We consider the use of hierarchical systems in modeling complex objects, taking critical decisions and creating MCSs. The three respective levels are called strata (hence stratification—division of a complex model into levels), layers and echelons. These terms are arbitrary but they define the type of the hierarchical systems. When speaking of systems in general without defining the type, the word "level" is used. For instance, two strata may be distinguished when modeling (describing) a computer: mathematical operations (programs, their elaboration) and physical (electronic) operations. The decision-making process in its general form may be regarded as comprising self-organization (selection of the decision strategy), instruction, adaptation and, finally, selection of the decision (preferable or possible).

Two-level systems. The elements of hierarchical system theory have been developed only for the two-level systems. These represent the simplest case but the authors of the theory hope to apply it

in the future to the multi-level systems. However, transition to the multi-level systems seems to encounter a lot of problems. We shall consider below a two-level process control system unless otherwise specified.

Information and control flows. The controlled process is fully characterized by its output Y. The input of the process is acted upon by external disturbance ω and a group of control signals m. Each local subsystem s_i manipulates signal m_i to control one x_ith component of production process P. The feedback signal on the actual

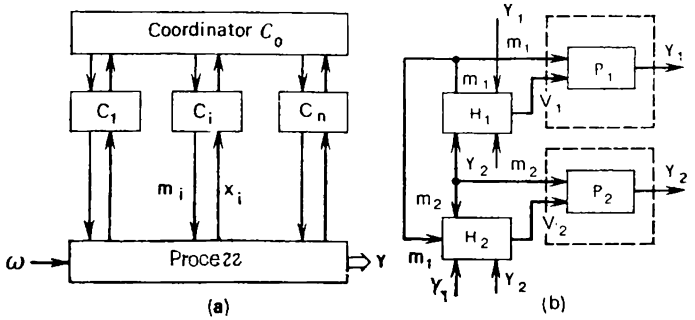


Fig. 5.5. Study of two-level hierarchical system
(*a*) representation of interaction; (*b*) division of process P into two subprocesses and formation of coupling function H; arrows show information requisite to form function H and input signals

value of said component is delivered to the respective control sub system. The superior system (coordinator) generates a coordinating signal γ for each subsystem. Subsystem s_i relays information w_i obtained from the subordinate systems and translated to a suitable form to the coordinator.

Three types of problems. Name the process control problem D a global problem, the subsystem problem D_i a local problem, and the top level problem D_0 a coordinator problem.

Subprocesses. Coupling function. Divide the process into n subprocesses so that each of them is controlled by its system s_i. The decomposition leads to the advent of additional inputs v_i in each of the subprocesses. These are intersubprocess *coupling inputs*. The depth of the coupling depends on the control actions exerted to all the subprocesses and on their outputs (Fig. 5.5). If

$$Y = \{y_1, y_2, \ldots, y_n\}, \quad M = \{m_1, m_2, \ldots, m_n\}$$

then

$$Y_i = H(M, Y) \tag{5.29}$$

Since the process output Y depends on control M and external disturbance $\Omega = \{\omega_1, \omega_2, \ldots, \omega_n\}$ and $Y = P(M\Omega)$, then $V = M, P(M\Omega)$.

The function H_i is called a coupling function of the subprocess. Implement one more function. As seen from the last formula, the coupling signals V_i are functionally dependent on the control actions M and external disturbances: $V_i = K_i(M\Omega)$. K_i is called a process interrelation function. Functions H_i and K_i are essentially similar.

Conflicts in two-level system. The hierarchical systems may give rise to conflicts. Distinguish two types of conflicts: inter-level and level conflicts. The first arise from the incompatibility of the global and local objectives. If the local objectives of the subsystems are incompatible and minimizing local costs by one element prevents that by the other element, the level conflict takes place. To eliminate the conflict the system should be consistent.

Coordination of subsystems. Coordination is effected by a superior control system. It also makes the subsystems act in concord to reach the objective of the system as a whole. This objective is essentially a solution of a certain global problem D of process control.

Two types of coordination. There are coordination of two types: lower subsystem—upper system and lower subsystem—controlled process. The first type resides in that the problems $\overline{D}_i$ handled by the subordinate subsystems are coordinated with respect to the superior problem D only when at least one pair of process entering variables X and γ is found whereat X is the solution of all partial subproblems $\overline{D}_i$ (with γ commanded from the upper level) and the global problem D is solved with the same γ. Mathematically, this can be written as a *sentence* (predicate):

$$\exists(\gamma, X)(P(X, \overline{D}_i(\gamma)) \text{ and } P(\gamma D)) \Rightarrow \text{true} \qquad (5.30)$$

where $\exists$ is the singularity quantifier substituting the expression "at least one pair ... is found"; predicate $P(X, \overline{D}_i(\gamma))$ reads: X is the solution of problem $\overline{D}_i$ at given γ; predicate $P(\gamma, D)$ reads: γ is the solution of problem D. If this sentence is true, the system can be coordinated. The second-type coordination takes place only if there is at least one pair γ and X whereat partial subsystem problems $\overline{D}_i$ are solved and simultaneously such a control $m_0(X)$ is ensured whereat the global process control problem D is solved. In other words, the lower-level elements can be coordinated if their objectives conform with each other. This statement may be formalized as

$$\exists(\gamma, X)(P(X, \overline{D}_i(\gamma)) \text{ and } P(m_0(X), D)) \Rightarrow \text{true} \qquad (5.31)$$

A compatibility postulate may be of help in estimating the system coordination.

Compatibility postulate. The local problems handled at a lower level are coordinated relative to the global problem of the process control, if they are coordinated with respect to the problems D_0 solved at the superior system level. That is, if the problems are compatible, the global objective is achieved when the superior element coordinates the subordinate systems for its objective.

Four problems of coordination. Distinguish four problems involved in coordination of the hierarchical systems.

1. *Synthesis of coordinator.* Let the global control problem D be known and the coordinator problem D_0 is to be found to make the system coordinatable. The problem is confined to determining the coordination principle, verifying the compatibility postulate and finding out whether the system coordinating signal is existent.

2. *Search of coordination algorithm.* Let the problem D_0 be selected and the system coordinated to the problem; find the algorithm for generating coordinating signal γ. Usually, the original coordinating signal is modified with the use of iteration.

3. *Modification of objective function.* Let the compatibility postulate be satisfied but the system be not coordinated to the problem D. It is necessary to change the problems handled by the lower subsystems so that they become coordinated to the problem D. It is customary in this case to isolate a new group of problems $D'(\gamma)$ for the lower subsystems so that it encompasses the initial problem $\overline{D}(\gamma)$

$$\overline{D}_i(\gamma) \subset D_i'(\gamma)$$

to satisfy the compatibility postulate and make exist the coordinating signal γ. The number of the lower-level problems (subsystems) may change. The problems are usually modified by modifying the local objective functions of the subsystems.

4. *Decomposition.* The global objective D is known. Find the superior-level problems D_0 and the subordinate problems so that the compatibility postulate is satisfied. The problem is confined to the three problems outlined above. It is necessary to select the coordination principle and the upper-level problem, then isolate and modify the subproblems and elaborate a method for finding the coordinating signal. Note, that the coordination holds a key position in all the problems.

Coordination principles. Each subsystem controlling the process pursues its own objectives and does not exchange data with other subsystems of its level. This may cause conflicts. The coordinator, while pursueing his own objectives, so affects the subsystems that the global objective is reached. The coordination may have two approaches.

Interrelation forecast. Sending the coordinating signals γ_k, the

centre simultaneously forecasts the values of coupling inputs $U_{i,k}$. If the control signals are so selected that the global objective is achieved and the actually obtained links fit in the forecast, the process is completed and the global problem is solved. The link coincidence may be estimated by the forecast and actual values of the process interrelation function K_i. The coordination process is usually iterative: the planner forecasts the links, finds the value of the control signal γ_k, then makes the lower system control the process, weights the importance of the links, determines a new value of signal γ_{k+1} and so on. The iteration process flows according to the formula

$$\gamma_{k+1} = \gamma_k + R(\alpha_k - F(m_k)) \tag{5.32}$$

where α_k is the forecasted importance of the link between the subsystems, $K(m_k)$ is the value of the subprocess interrelation function at the kth step; F is a conversion applicable to the error between the forecasted and actual values of the link.

To accelerate the process, the coupling signal trend can be forecasted for which purpose function K is interpolated.

Interrelation decoupling. Each subordinate element is entitled to solve its problem with regarding the coupling inputs as additional free variables, i.e. the subprocesses are considered to be fully decoupled. The coordination is confined to the elimination of discrepancy between the actual and desirable interrelations of the subsystems. Notice, that the coordinator can affect the subsystem only by changing the local objective functions (e.g. changing payments for resources). There are no other methods of acting upon the subsystems.

Two types of system coordination. The systems where the control signal is not applied to the input of the controlled process before the final value of the correcting signal γ is found by iteration are polyphase operating systems. If the control signal is fed at each iterated value of γ_k, the systems are the linear correction systems. The latter are often used for real-time application.

Accounting for constraints. Restriction of the controlled variables M brings about considerable difficulties in coordination of the hierarchical systems. For instance, if in the absence of constraints a system is coordinatable (e.g. on the matching principle) and M_o is the only global control action, such a coordination method can be inapplicable if the constraints are so imposed that M_o is not a permissible control. On the contrary, the coordination principle that cannot be used with a given system without constraints may become applicable if the local solutions are suitably restricted. The principles of coordination of the hierarchical control systems described here are widely used in power industry in particular to control operation of integrated systems.

Part Two

OPTIMAL OPERATION OF ELECTRIC POWER SYSTEMS AND PLANTS

6

OPTIMAL DISTRIBUTION OF LOAD IN POWER SYSTEM

6.1. Rational Control of Power System

One of the basic goals of optimization of a power system under normal operation conditions is to optimize distribution of loads among the generators of the system. The optimization presupposes a highly efficient utilization of the energy, labour and monetary resources, reliable and uninterrupted supply, satisfaction of various auxiliary requirements put forward by many branches of national economy.

The extreme complexity of the goal stems from large scale and intensive development of power production, non-uniform technical, economical and operation characteristics of separate segments of the power systems (power plants, transmission lines). A practical and effective tool for achieving the said goal has been provided by the advent of MCSs based on modern computers. However, even computerization requires breaking down of the problem into a set of simpler interrelated subproblems to yield positive results.

At present the power systems become analogs of large cybernetic amalgamations whose effectiveness and reliability should be estimated from the point of view of the national economy. Thus, the problem sets forth multiple objectives and has to be solved with the use of multiple criteria. No practical methods of solving such a problem in power industry have been yet elaborated so it is handled as a single-objective in view of the adopted hierarchy of control.

The load distribution optimization problem is decomposed according to the temporal, spatial and situational types of hierarchy.

Spatial hierarchy has four levels, hence four variants of problems.

The *first level* is the optimal distribution of loads between the pools of the USSR power grid, determination of inter-system transfers and load curves for separate power systems.

The method of equivalent networks, generator and load nodes is used at this level. The power systems or groups of power plants are represented by equivalent characteristics of, e.g., system operat-

ion cost versus power or equivalent fuel total consumption versus power of a group of TPPs, etc. The techniques for plotting the equivalent characteristics are given in Ch. 7.

Each hydro plant is also represented in terms of equivalents, but they cannot usually be applied to a group of hydro plants because of different heads and rates of water-discharge.

The *second level* is the optimal distribution of loads between the power systems of a pool (IPS) and large plants with scheduling loads of the regional power systems (RPS) and power transmission lines of the pool. Likewise, the equivalence technique is employed with accounting for the different structure of the pool.

The *third level* is the optimal distribution of loads between the RPS plants, calculation of load of the electric networks. Load schedules of separate plants and networks are elaborated. The equivalence method is applied to the power-generating units and network facilities. Separate power plants or large units are represented by their energy characteristics.

The *fourth level* is the distribution of loads among the power-generating units. No equivalence technique is used. The unit powers are determined in view of auxiliary power consumption.

All the levels are interconnected. The plant loads, power flows, and other parameters for any lower level are determined at a higher level. At the same time, the equivalent calculations at the upper levels are carried out with account of specifications and parameters of separate elements and nodes of the power system, defined at the lower levels. Finally, some solutions linked with spatial decomposition can be refined by iteration through the use of feedbacks between the fourth and any other superior levels.

Temporal hierarchy is normally made up of three levels hence handles three types of problems.

1. Elaboration of long-term plans (from a month to a year) with plotting the forecasted characteristic load curves for PG, IPSs, RPSs and separate plants. The forecast is based on the entire source information so that minor details of the system are either ignored or approximated. Such calculations are aimed at determining the operating conditions needed to plan technical and economic measures.

2. Elaboration of short-term plans (from a day to a month) with scheduling the load curves for PG, IPSs, RPSs and separate plants. At this level, all the particulars and characteristics of the system are taken into account. The load curves plotted for normal operating conditions make primal contribution to the effectiveness of the system. However, the probabilistic nature of loads may cause refinements in the schedule where the reliability becomes superior to effectiveness considerations. Refinement is performed at the third level.

3. Real-time regulation of plant capacities involves automatic frequency and active power control, voltage and reactive power control, regulation of power flows, real-time supervision of power system operation, network switchings, equipment outage for repair, manipulation of the standby, etc. Thus, these calculations are aimed at updating the scheduled operation of the power system.

Situational hierarchy allows considering the problems of load distribution under normal, emergency, and post-emergency conditions of the system. Naturally all economy considerations are neglected in case of emergency. The principal task under such conditions is to elevate the reliability to the highest possible level and obtain energy of rated quality. Post-emergency conditions provide for solving some problems of optimal load distribution. This book deals only with the problems of normal operation.

The decomposition based on the hierarchical structure of the power industry control does not make the system load optimization an easy job. The problem is still very complex. Its algorithms are bulky, require various and often labour-consuming mathematical methods, the processing programs necessitate high memory capacities and long computer time so that they can be handled only by large machines. All these make the planner simplify the problems especially if the inevitable degrading of precision can be tolerated. The most significant particular solutions to this problem depend on the structure of the power system.

For all-thermal power systems (the systems comprising only TPPs) there are no energy resource restrictions under normal conditions. Actually if the plant is furnished with the rated fuel reserve, it can run full available or installed capacity. The optimization period in such a system can correspond to any time period. Usually an hour is used for the purpose. If operation is optimized for a longer period it is assumed that the calculated intervals inside the period are independent.

The mixed hydro-thermal systems are characterized by the hydro plant restrictions for the water storage energy resources. The use of water resources is limited during a day, week, month or year depending on the hydro plant rate of discharge regulation period. This involves integral constraints of the rate of discharge during the calculated period. The calculated interval of optimization is usually a part of the optimization period.

Other approaches are also possible. For instance, sometimes it is possible to neglect the active power losses in the networks or assume that they do not affect the nodal voltage, etc.

This chapter will discuss the methods of optimal distribution of daily load between the power plants and generators included in the third level of spatial hierarchy and in the second level of temporal hierarchy considered above. Notice that the problem is solv-

ed for the given operating equipment of the plants; selection of optimal equipment is covered in Ch. 8.

The economic indices of a system depend on the distribution of active and reactive powers. Generation and distribution of active and reactive powers are intimately interrelated. For instance, distribution of reactive powers determines nodal voltage and active power losses in the networks. This in turn affects the active power flows and fuel consumption at different plants. Thus the system load distribution problem has a plurality of facets which drastically complicate the task. In fact, a single algorithm should cover operation of separate plant generators, power flows in the electric system, loading of synchronous and static condensers. Knowing the complexity of the system, the awkwardness and frequently insolubility of such a problem become obvious.

Therefore a common practice is to substitute this complex problem by two simpler subproblems: optimal distribution of active loads in the system at constant nodal voltage and active power loss approximation, and calculation of network operation at fixed active powers of generator nodes.

With such an approach, first are determined the active powers of generator nodes with the approximation of operating conditions and power losses in electric networks. Then the second subproblem is solved to find the active powers in the generator nodes, while their reactive powers are determined by the criterion of the minimum active power losses in the networks. Thus the problems of optimal distribution of active and reactive powers are solved separately.

Breaking down the global optimization problem into two independent subproblems decreases the size and awkwardness of the algorithm, the required memory capacity and computer time. Since the source information used in optimization involves gross errors, such an approach affects but slightly the precision of the calculation results. Another argument in support of individual solution of these subproblems is the need for their periodical handling during operation of the power systems. Distribution of resistive loads is scheduled daily for the coming day. The second subproblem is solved only for characteristic operating conditions of the electric network; besides there are no satisfactory methods by now for forecasting reactive loads.

At present there exist methods and routines for solving the complex problems, which are applied to some power systems for detailed analysis of system operation (Sec. 6.8).

Sections 6.2 through 6.7 will cover the simplest methods of optimal distribution of loads for some typical cases (TPPs, HPs, PSPs, NPPs, etc.). These methods are based on the method of Lagrange multipliers which cannot be applied to all the problems of practical operation. In particular they can cope with the problem if the con-

straints are in the form of equations, or if the function is separable and the constraints into only independent variables are in the form of inequalities (e.g. limit capacities of power plants). These methods of load optimal distribution cannot account for the constraints into the dependent variables in the form of inequalities (e.g. transmission line capacity). The concept of general methods for solving the complex problem is given in Secs. 6.8 and 6.9.

Consider the basics of the Lagrange method of multipliers. Let be given objective function $F(X_1, X_2, \ldots, X_n)$, the extremum of which is to be found. Variables $(X_1, X_2, \ldots, X_n)$ are interrelated by k constraint equations:

$$\left.\begin{aligned} W_1(X_1, \ldots, X_n) &= 0 \\ W_2(X_1, \ldots, X_n) &= 0 \\ \cdots\cdots\cdots\cdots & \end{aligned}\right\} \tag{6.1}$$

When using the Lagrange multipliers, the extremum of function $F(X_1, \ldots, X_n)$ is replaced with the extremum of a special function Φ (Lagrange function) which includes the objective function and the constraint equations

$$\Phi = F + \sum_{i=1}^{k} \lambda_i W_i \tag{6.2}$$

The constant factors λ_i are called the Lagrange undetermined multipliers. Differentiating the function with respect to independent variables $(X_1, \ldots, X_n)$ and reducing partial derivatives to zero, we find the extremum of the function

$$\left.\begin{aligned} \frac{\partial \Phi}{\partial X_1} &= \frac{\partial F}{\partial X_1} + \sum_{i=1}^{k} \lambda_i \frac{\partial W_i}{\partial X_1} = 0 \\ \cdots\cdots\cdots\cdots & \\ \frac{\partial \Phi}{\partial X_n} &= \frac{\partial F}{\partial X_n} + \sum_{i=1}^{k} \lambda_i \frac{\partial W_i}{\partial X_n} = 0 \end{aligned}\right\} \tag{6.3}$$

Variables $X_1, \ldots, X_n$ and multipliers λ_i are unknown (n and k, respectively, thus $n + k$ unknowns). The number of equations from which they can be found is also $n + k$, i.e. n equations (6.3) and k equations (6.1). Thus it is possible to find agruments corresponding to the extremum of the Lagrange function Φ and characterizing the extremum of the objective function F.

We next check the sign of the second derivative of function F or Φ. If $d^2F > 0$ or $d^2\Phi > 0$, the extremum is minimum.

If solving the set of equations infringes the constraints for minimum or maximum values of X_i, the respective X_i is equated to the limit value.

6.2. Load Distribution Between Thermal Power Plants

Consider an electric power system of thermal power plants and the distribution of active loads between TPPs in view of active power losses in the network. The system comprises $i=1, 2, \ldots, n$ thermal power plants for which consumption characteristics $B_i\ (P_{TPP,i})$ and total load P_Σ are known.

1. Objective equation

$$B = B_1\ (P_{TPP,1}) + B_2\ (P_{TPP,2}) + \ldots + B_n\ (P_{TPP,\,n}) \Rightarrow \min \tag{6.4}$$

2. Coupling equation $B_i\ (P_{TPP,i})$.
3. Constraints—power balance equations

$$\sum_i P_{TPP,\,i} - P_\Sigma - \pi = 0 \tag{6.5}$$

where π is the total loss of active power.

4. Derive the optimization equation. The Lagrange function

$$\Phi = (B_1 + B_2 + \ldots + B_n) + \lambda \left(\sum_i P_{TPP,i} - P_\Sigma - \pi\right) = 0 \tag{6.6}$$

Since the expression in the second parentheses is equal to zero, the minima of the Lagrange function (6.6) and of the objective function (6.4) coincide.

Differentiating the Lagrange function with respect to variables $P_{TPP,1}, \ldots, P_{TPP,n}$ and setting the derivatives to zero, we obtain

$$\left.\begin{aligned} \frac{\partial \Phi}{\partial P_{TPP,\,1}} &= \frac{\partial B_1}{\partial P_{TPP,\,1}} + \lambda_1 \left(1 - \frac{\partial \pi}{\partial P_{TPP,\,1}}\right) = 0 \\ &\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \frac{\partial \Phi}{\partial P_{TPP,\,n}} &= \frac{\partial B_n}{\partial P_{TPP,\,n}} + \lambda_n \left(1 - \frac{\partial \pi}{\partial P_{TPP,\,n}}\right) = 0 \end{aligned}\right\} \tag{6.7}$$

As transpires from (6.7)

$$\frac{\dfrac{\partial B_1}{\partial P_{TPP,\,1}}}{1 - \dfrac{\partial \pi}{\partial P_{TPP,\,1}}} = \ldots = \frac{\dfrac{\partial B_n}{\partial P_{TPP,\,n}}}{1 - \dfrac{\partial \pi}{\partial P_{TPP,\,n}}} \tag{6.8}$$

Let us denote $b_i = \dfrac{\partial B_i}{\partial P_{TPP,n}}$ the incremental rate of fuel consumption showing how the amount of fuel consumed by the i th plant will change if its load is changed by $\partial P_{TPP,\,i}$; $\sigma_i = \dfrac{\partial \pi}{\partial P_{TPP,i}}$ the incremental rate of active power losses in networks, i.e. the value illustrating how the network losses will change if the power of the ith plant changes by $\partial P_{TPP,i}$.

Using this notation, obtain the conditions of optimal load distribution

$$\mu = \frac{b_i}{1-\sigma_i} = \text{idem} \tag{6.9}$$

If (6.9) is satisfied, function (6.6) will be minimum only if $\frac{\partial^2 B_i}{\partial P^2_{TPP,i}} \geqslant 0$ or $\frac{\partial b_i}{\partial P_{TPP,i}} \geqslant 0$. This means that the characteristics of incremental rates should be monotonous.

The energy characteristics of power plants and units usually fail to meet the above requirements and should be "corrected" using special techniques.

If the active power losses are neglected, i.e. at $\pi = 0$, the condition of optimal distribution of load takes the form

$$b_i = \text{idem} \tag{6.10}$$

Let us discover the physical sense of condition (6.9). Write down (6.9) in finite differences and multiply the numerator and denominator by ΔP_{TPP}, i.e.

$$\frac{\frac{\Delta B}{\Delta P_{TPP}} \Delta P_{TPP}}{\left(1 - \frac{\Delta \pi}{\Delta P_{TPP}}\right) \Delta P_{TPP}} = \frac{\Delta B}{\Delta P_{TPP} - \Delta \pi} = \frac{\Delta B}{\Delta P_a} = \text{idem}$$

where ΔP_a is the active power received by the consumer.

It is seen from (6.10) that at optimal distribution of load, fuel costs ΔB for the power ΔP_a received by the consumer should be equal for all the plants.

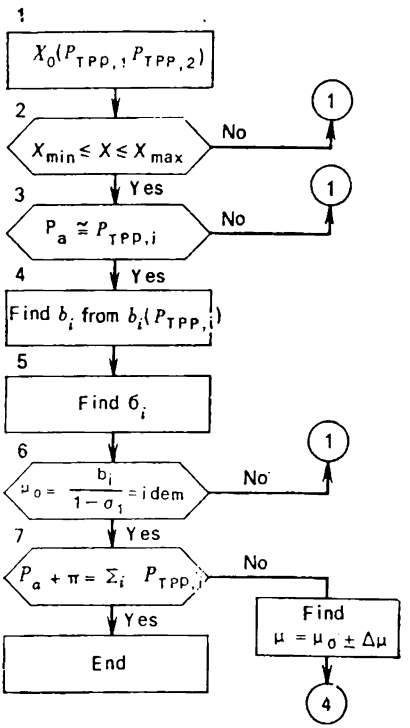


Fig. 6.1. Generalized flow chart of algorithm for optimal distribution of load in thermal power system

In 3 $P_a \cong \Sigma P_{TPP,i}$

Figure 6.1 shows a flow chart for solving this problem. The calculations are as follows.

Blocks 1-3. Find arbitrary distribution of loads between system plants X ($P_{TPP,1}$, . . ., $P_{TPP,m}$). Now the constraints (block *2*) and active power balance (block *3*) are satisfied and the network losses are neglected.

Block 4. Find incremental rates of fuel consumption b_i for powers X. Since the plant operating conditions are set arbitrarily, $b_i \neq \neq$ idem.

Block 5. Determine incremental rates of active power losses σ_i for the known powers X which involve calculation of the system operating conditions.

Block 6. Change the value of X to satisfy the optimality condition

$$\mu = \frac{b_i}{1-\sigma_i} = \text{idem}$$

with observing the permissible plant power constraints.

If constraints $P_{TPP,i,\min} \leqslant P_{TPP,i} \leqslant P_{TPP,i,\max}$ are violated, the power of the respective plant is equated to the boundary value and is considered forced. Only the generator nodes with the satisfied constraints are subject to optimization.

Block 7. Check system power balance. If at $\mu_0 = \text{idem}$, $\sum_i P_{TPP,i} > P_\Sigma + \pi$, find a new incremental rate of the system $\mu = \mu_0 - \Delta\mu$. If $\sum_i P_{TPP,i} < P_\Sigma + \pi$, then $\mu = \mu_0 + \Delta\mu$. The calculation technique of block *4* is used to determine new active power conditions at $\mu = \text{idem}$. The calculations are carried out till equation (6.5) is satisfied.

6. After (6.5) and (6.9) are satisfied, start calculations with block *5* to refine σ_i and subsequent calculations.

7. The conditions will be optimal if $\mu = \text{idem}$ according to (6.9), while (6.5) is satisfied.

Optimal distribution of load neglecting active power losses. Such a problem is more typical of a load distribution between the power-generating units than of the power system. However, it can be encountered in systems with a high degree of power concentration since neglecting the network power losses does not cause gross errors.

Since $\pi = 0$, it follows that $\sigma_i = 0$ and the optimization equation takes the form (6.10), i.e. $b_1 = b_2 = \ldots = b_n$ or $b_i = \text{idem}$. The optimal operation corresponds to the equality of the incremental rates of the plants.

Condition (6.10) holds true for the hydraulic units, turbines and boilers of TPPs. In case of a group of units operating in parallel, it is also necessary to find equal incremental rates which will minimize the objective function.

The principle of equality of relative increments is explained as follows (Fig. 6.2). If the incremental rates of two operating units having powers P_1 and P_2 and rising curves b_i $(P_{TPP,i})$ are not equal to each other, *unit 1* which has a lower incremental rate, will be under better conditions. Since this unit is more effective than the

other, it should be additionally loaded with ΔP at the expense of the other for more economic operation. However, after unit *1* is loaded with ΔP, its relative increment drops to b_1', while that of *unit 2*

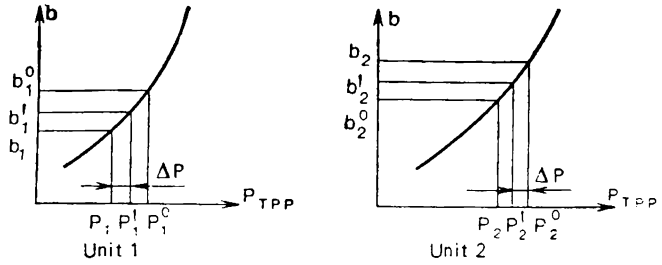


Fig. 6.2. Optimality ensured by equal relative increments

reduces to b_2'. As soon as the incremental rates are equal to each other (loads P_1^0, P_2^0), no additional redistribution of load will give any economy and the conditions may be regarded optimal.

6.3. Load Distribution in Hydro-Thermal Power System

The problem of optimal distribution of load in a mixed system with both thermal and hydro power plants is divided into two subproblems.

The first subproblem is to optimize long-term operation of the system. This subproblem covering the entire regulation cycle of the hydro plant is aimed at finding the optimal distribution of loads between the system plants by optimizing utilization of the reservoirs of water resources. The calendar terms of draw-down and filling of reservoirs are scheduled for all the plants of the system. These are specific tasks which are discussed in Ch. 9.

Such calculations are used to regulate water resources for short-term cycles. For instance, if a plant features an annual run-off regulation, the resources (run-off) constraints will be determined for a month, a week, and a day.

The second subproblem, which will be discussed here, is optimization of short-term operation or load distribution in the mixed system for a period of 24 hours or less. Constraints into the river run-off are determined when solving the first subproblem.

The short- and long-term operations of hydro plants are of course intimately interrelated but the algorithmic and computational difficulties preclude including the said problems into one algorithm. The reason for such a division, apart from different objectives and algorithms, is a drastic difference in the completeness and validity of the source data. In case of a daily or even weekly period, the in-

formation is valid enough for practical purposes. The river inflow, system load, plant equipment, etc. can be predicted to a sufficient accuracy for such periods. If the periods are long, the information is of a probabilistic or stochastic nature. Difference in completeness, form and validity of the source data necessitates the use of different methods for solving the said problems. Besides, integration of such problems would radically complicate the optimization algorithms.

Distribution of load at constant water head. It is assumed that the head remains constant throughout the optimization period though the plant carries out its regulation. Such an assumption holds good for high- and medium-head hydro stations, when head fluctuations caused by the varying water levels do not introduce any notable errors in the energy indices of the plant.

As it will be seen below, the assumption of the constant head considerably simplifies the problem algorithm. The energy of one cubic metre of water is virtually constant for the entire period of optimization. Actually, the hydro station energy is $E = 9.81QH\eta$, and at $H = \text{const}$ $E \approx kQ$, where $k = 9.81H\eta$; the hydro plant efficiency η is high and cannot materially change the energy. The effect of the head is dozens of times greater.

The simplest algorithm is based on the Lagrange multiplier technique.

Statement of the problem. Let a system include one equivalent thermal power plant and j — $\alpha, \beta, \ldots, \gamma$ hydro plants. Each hydro plant can utilize a definite amount of water (run-off) during the period T. The task is to optimize the load distribution between the plants for each calculated interval of the entire period T.

1. Objective equation

$$B = \sum_{t=1}^{t=k} B_t \Delta\tau_t \Rightarrow \min \qquad (6.11)$$

The fuel consumption B_t by the equivalent thermal plant depends on its output over each calculated time interval $t = 1, 2, \ldots, k$, hence on the power of the hydro plants.

2. Coupling equations are the energy consumption characteristic B (P_{TPP}) of the equivalent thermal power plant and those of each hydro plant, Q_j (P_j, H_j).

3. Constraint equations.

A power balance equation for each calculated interval (k equations) is as follows:

$$W_{P,t} = P_t - (P_{TPP,t} + P_{\alpha,t} + P_{\beta,t} + \ldots + P_{\gamma,t}) + \pi_t = 0 \qquad (6.12)$$

A discharge rate constraint is set for each hydro plant (j equations in all)

$$W_j = W_{Q,\,j} - \sum_{t=1}^{t=k} Q_{j,\,t}\,\Delta\tau_t = 0 \tag{6.13}$$

In Eqs. (6.12) and (6.13)

$P_t = P_1,\ P_2 \ldots$ = system load during a time interval $t = 1,\ 2,\ \ldots,\ k$

$P_{TPP,\,t}$ = thermal power plant power

$P_{\alpha,t},\ P_{\beta,\,t},\ \ldots,\ P_{\gamma,t}$ = hydro plant powers

π_t = active power losses in networks

$W_{Q,j} = W_{Q,\,\alpha},\ W_{Q,\beta} \ldots$ = run-off constraints

$Q_{j,\,t} = Q_{\alpha,\,t},\ Q_{\beta,t} \ldots$ = hydro plant discharge rate over each calculated tth time interval, $\Delta\tau_i$

4. The optimization equation is as follows:

$$\frac{b}{1-\sigma_{TPP}} = \lambda_j \frac{q_j}{1-\sigma_j} \tag{6.14}$$

where $b = \dfrac{\partial B_{TPP}}{\partial P_{TPP}}$ = incremental rate of fuel consumption of the thermal power plant

$q_j = \dfrac{\partial Q_j}{\partial P_j}$ incremental rate of discharge of the jth hydro plant

$\sigma_{TPP} = \dfrac{\partial \pi}{\partial P_{TPP}}$, $\sigma_j = \dfrac{\partial \pi}{\partial P_j}$ = incremental rates of the active power losses in the electric networks at variations of TPP and HP powers respectively

Derivation of optimization equation. The Lagrange function comprises Eqs. (6.11)-(6.13) and has the form

$$\Phi = \sum_{t=1}^{t=k} B_t + \sum_{t=1}^{t=k} \lambda_t W_{P,\,t} + \sum_{j=\alpha}^{j=\gamma} \lambda_j W_j \tag{6.15}$$

The unknowns are the powers of TPPs and each jth HP over each calculated tth time interval, $jt + t$ unknown powers in all. The Lagrange multipliers are also unknowns: t multipliers λ_t and j multipliers λ_j. Thus the number of unknowns is $jt + 2t + j$. To solve the problem, write $jt + 2t + j$ equations.

If the Lagrange function (6.15) is differentiated with respect to independent variables, we obtain $jt + t$ equations. Partial derivatives of (6.15) are taken with respect to the powers $P_{TPP,1},\ P_{TPP,2}, \ldots,\ P_{TPP,\,k},\ P_{\alpha,\,1}, \ldots, P_{\alpha,\,k}, \ldots, P_{\gamma,k}$.

Solving these equations, we find $jt + t$ unknowns. The run-off balance equations give j equations, while the power balance equa-

tions t equations. Thus, the number of equations is sufficient to find the unknowns.

The TPP power derivatives are

$$\frac{\partial \Phi}{\partial P_{TPP,\,t}} = \frac{\partial B_t}{\partial P_{TPP,\,t}} + \lambda_t \left(1 - \frac{\partial \pi_t}{\partial P_{TPP,\,t}}\right) = 0 \qquad (6.16)$$

$$-\lambda_1 = \frac{b_1}{1-\sigma_1}, \quad -\lambda_2 = \frac{b_2}{1-\sigma_2}, \quad \ldots, \quad -\lambda_k = \frac{b_k}{1-\sigma_k} \qquad (6.17)$$

The HP power derivatives give the equations

$$\frac{\partial \Phi}{\partial P_{j,\,t}} = \lambda_t \left(1 - \frac{\partial \pi}{\partial P_{j,\,t}}\right) + \lambda_j \frac{\partial Q_{j,\,t}}{\partial P_{j,\,t}} \qquad (6.18)$$

Solving (6.18), we obtain

$$\left.\begin{aligned} -\lambda_1 &= \frac{\lambda_\alpha q_{\alpha,\,1}}{1-\sigma_{\alpha,\,1}} = \frac{\lambda_\beta q_{\beta,\,1}}{1-\sigma_{\beta,\,1}} = \ldots = \frac{\lambda_\gamma q_{\gamma,\,1}}{1-\sigma_{\gamma,\,1}} \\ -\lambda_2 &= \frac{\lambda_\alpha q_{\alpha,\,2}}{1-\sigma_{\alpha,\,2}} = \frac{\lambda_\beta q_{\beta,\,2}}{1-\sigma_{\beta,\,2}} = \ldots = \frac{\lambda_\gamma q_{\gamma,\,2}}{1-\sigma_{\gamma,\,2}} \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \end{aligned}\right\} \qquad (6.19)$$

Solving (6.17) and (6.19), we obtain the optimization conditions

$$\left.\begin{aligned} -\lambda_1 &= \frac{b_1}{1-\sigma_1} = \frac{\lambda_\alpha q_{\alpha,\,1}}{1-\sigma_{\alpha,\,1}} = \frac{\lambda_\beta q_{\beta,\,1}}{1-\sigma_{\beta,\,1}} = \ldots \\ -\lambda_2 &= \frac{b_2}{1-\sigma_2} = \frac{\lambda_\alpha q_{\alpha,\,2}}{1-\sigma_{\alpha,\,2}} = \frac{\lambda_\beta q_{\beta,\,2}}{1-\sigma_{\beta,\,2}} = \ldots \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \end{aligned}\right\} \qquad (6.20)$$

All the quantities included in (6.20), except the Lagrange multipliers, are determined by the electric parameters of the equipment (incremental rates of fuel consumption b and water discharge q of TPPs and HPs, respectively) and the parameters of the electric network (incremental rates of power losses σ) so that all the time indices may be omitted to write the optimization equation in the final form

$$\frac{b}{1-\sigma} = \lambda_\alpha \frac{q_\alpha}{1-\sigma_\alpha} = \lambda_\beta \frac{q_\beta}{1-\sigma_\beta} = \ldots = \lambda_\gamma \frac{q_\gamma}{1-\sigma_\gamma} \qquad (6.21)$$

Condition (6.21) has the following meaning: to optimize load distribution, it is necessary to observe constant ratio λ between TPPs and HPs throughout the optimization period. The load should be distributed between a TPP and an HP α as follows

$$\lambda_\alpha = \left(\frac{b}{1-\sigma}\right)\left(\frac{q_\alpha}{1-\sigma_\alpha}\right)^{-1} \qquad (6.22)$$

The ratio between a TPP and an HP β is equal to

$$\lambda_\beta = \left(\frac{b}{1-\sigma}\right)\left(\frac{q_\beta}{1-\sigma_\beta}\right)^{-1}, \quad \text{etc.}$$

Concurrently (6.12) should be satisfied.

The values λ_α, λ_β, . . ., λ_γ correlate operation of TPP and the respective HP. The hydro plants may differ in the head and discharge, therefore each of them has its particular multiplier λ. The nature of interrelations between the multiplier λ and the hydro plant parameters is explained below.

Dimensions and physical sense of Lagrange multipliers. Let us consider a simplest mixed system comprising a TPP and an HP. The condition for optimal distribution of load in such a system is

$$b = \lambda q \tag{6.23}$$

Knowing that $b = \frac{\Delta B}{\Delta P_{TPP}}$, $q = \frac{\Delta Q}{\Delta P_{HP}}$, we find

$$\lambda = \left(\frac{\Delta B}{\Delta P_{TPP}}\right)\left(\frac{\Delta Q}{\Delta P_{HP}}\right)^{-1}$$

Assume that power increments for both plants are equal, i.e. $\Delta P_{TPP} = \Delta P_{HP}$, then

$$\lambda = \frac{\Delta B}{\Delta Q} \tag{6.24}$$

Thus, λ is the measure of effectiveness of water resource utilization in the system. This coefficient indicates the fuel economy ensured if the hydro plant utilizes discharge ΔQ. Obviously, the optimal conditions are those when the water resources of each hydro plant are utilized to the same effectiveness throughout the optimization period. Thus the optimal distribution during the said period is at

$$\lambda = \text{idem} \tag{6.25}$$

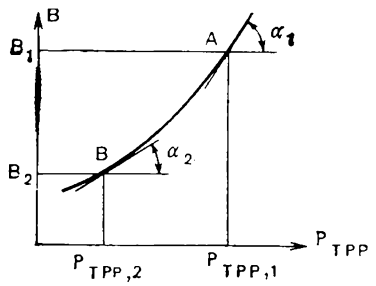


Fig. 6.3. Operation of thermal plants vs HP discharge rate

The coefficient λ is linked with the hydro plant parameters, i.e. with its head and discharge since the discharge energy ΔQ depends on the head. Let us first consider the relation when the head H = const. Let the system load P be distributed between the plants ($P = P_{TPP,1} + P_{HP,1}$). With such a distribution the thermal power plant fuel consumption is B_1 (Fig. 6.3) and the fuel consumption incremental rate at point A, $b_1 = (\Delta B_1)\,(\Delta P)^{-1} = \tan \alpha_1$. Run-off utilization factor $\lambda = b_1\,(q)^{-1}$.

Now consider such a power balance when HP operates with a greater power, $P_{HP,2}$, i.e. $P = P_{TPP,2} + P_{HP,2}$. Obviously with $P_{HP,2}$ the discharge rate increases and $Q_{HP,2} > Q_{HP,1}$. The thermal power

plant has the fuel consumption B_2 (point B) and its incremental rate $b_2 = \Delta B_2 (\Delta P)^{-1} = \tan \alpha_2$. Thus $b_2 < b_1$ and $\lambda_2 < \lambda_1$. Hence the effectiveness of water resource utilization in the system is inversely proportional to the discharge rate of the hydro plant. Actually, if HP operates at low discharge rates and power, the non-economical thermal power plants are also engaged in the system. Each cubic metre of water saves fuel by unloading the non-economical thermal

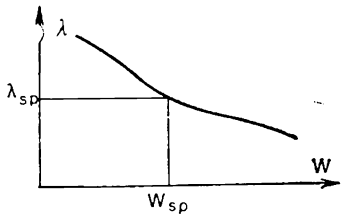


Fig. 6.4. Value of λ vs HP discharge

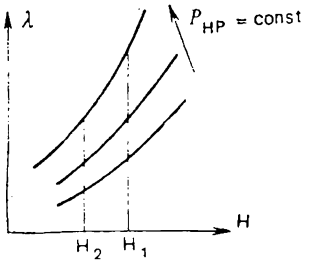


Fig. 6.5. Value of λ vs HP head

equipment. If the hydro plant operates at high discharge rates and power, TPP fuel is saved, so that λ diminishes.

As seen from (6.13), the HP discharge rate constraints are introduced in the problem being discussed. The coefficient λ should correspond to the specified discharge (Fig. 6.4). This problem is solved by inspection.

The coefficient λ is directly proportional to the head of HP. Actually, if HP operates with a constant power P_{HP}, and its heads H_1 and H_2 differ from each other, then with $H_1 > H_2$, $Q_1 < Q_2$ (Fig. 6.5).

Generalized flow chart of algorithm for distributing load at HP constant head. To optimize load distribution by the Lagrange technique, it is necessary to select the coefficient λ according to the specified discharge rate of HP and to find such a pattern for distributing load whereat λ = idem for the entire period. The uncertainty of λ at the beginning of the problem necessitates iteration. The iteration procedure is shown in the flow chart of Fig. 6.6 which is drawn for a mixed system comprising an HP and a TPP.

Given are system loads P_1, P_2, . . ., P_k for the calculation time intervals $t = 1, 2, \ldots, k$; the HP discharge rate Q (P_{HP}) and the TPP fuel consumption B (P_{TPP}); characteristics of power plants incremental rates q (P_{HP}) and b (P_{TPP}); constrains into discharge W_{sp} and powers of the plants. The electric system substitution is also given.

Blocks 1-3. Specify the hydro plant load $P_{HP.1}$ for $t = 1$ and check whether it is permissible. If the HP powers do not satisfy the constraints, they are adjusted with $\pm\Delta P$ increment.

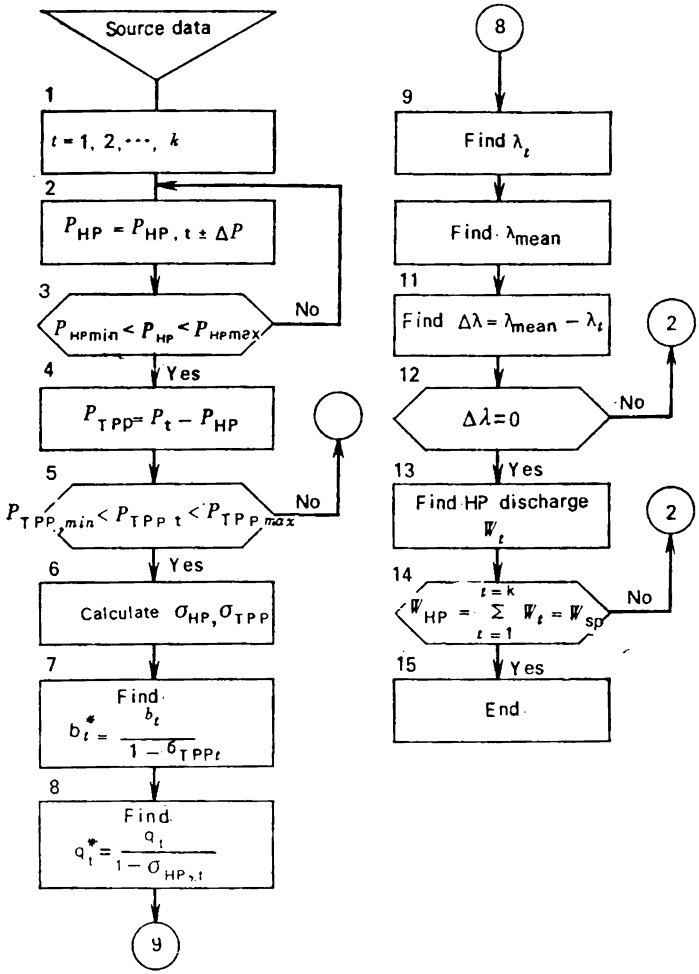


Fig. 6.6. Generalized flow chart of algorithm for optimal load distribution in hydro-thermal system

Blocks 4 and 5. Determine the TPP power from the balance equation and check whether it is permissible. If it is impermissible, adjust the HP power and return to block *2*.

Block 6. Calculate the network conditions and relative increment of losses.

Blocks 7 and 8. Calculate the relative increments in view of σ for an initial arbitrary and generally non-optimal distribution of load for all the time intervals $t = 1, 2, \ldots, k$.

Blocks 9 and 10. Calculate coefficients λ_t for each t. Since the load distribution was arbitrary, coefficients λ are different, i.e. the

operation is not optimal. The values of λ should be set to the average level λ_{mean}.

Blocks 11 and 12. Equate λ_t and λ_{mean}, depending on the sign of the difference $\Delta\lambda=\lambda_{mean}-\lambda_t$ with power increment $\pm\Delta P$. Start calculations from block *2* each time. If the conditions of block *12* are satisfied, the operation is permissible and λ = idem but cannot be regarded optimal before the discharge constraint is checked.

Blocks 13 and 14. If the HP discharge $W_{HP} = W_{sp}$, the problem is solved; if not, the HP power is changed with a pitch of $\pm\Delta P$ depending on the sign of the difference $\Delta W = W_{sp} - W_{HP}$ and calculations are restarted from block *2*.

This flow chart is so simple only for particular applications to small power systems. In case of large systems, the need for multiple iterations violates the convergence of the computing process or drastically increases the time required for calculations. In such an event, it is common to use algorithms based on gradient methods which involve particular technique to ensure the convergence of the process.

Load distribution at variable head of HP. The HP head in short-term control can vary because of unstable level of the head and tail waters. The medium- and high-power dam hydro plants have the water reservoirs of sufficient capacity so that the head water level changes but slightly during a day (except the flooding). At the same time, these plants operate in the peak-load part of the system load curve, regulate frequency, and serve as on-line standby which causes a substantial variation in their powers, hence in the tail water level. The tail water variation at the Kama Hydro is 3.5 m during a day, at the Novosibirsk Hydro, 2.5 m, and so on. At the diversion dam hydro plants, the head changes primarily due to fluctuations of the head water level.

The head changes may amount to several percent. In such an event, the heads during the next time intervals are determined by the hydro plant operation in the current interval. The head changes caused by the head water are found when calculating the water energy regulation; the non-stationarity of the process is insignificant and can be neglected. If the head changes stem from the tail water, it is necessary to allow for the unsteady conditions in the tail water which stabilize slowly, radically complicating the calculations because the after-effect period may reach ten or more hours.

Derivation of condition for optimal distribution of load in view of HP head variations. Let the system comprise two plants: a hydro and a thermal power plant. A preset load schedule is arbitrarily distributed between them with observing the power balance. The HP discharge curve is determined from the HP power graph (Fig. 6.7).

Redistribute the load and see which changes in the system may result. Increase the HP discharge at the moment t_a of the interval

dt by dQ, then decrease the discharge at the moment t_b of the interval dt by the same value dQ. How will the powers of the plant change in the period between t_a and t_b? An increase in the discharge will lead to an increase in the power $dP_a = dQq_a^{-1}$ and to the respective decrease in the power of the thermal plant.

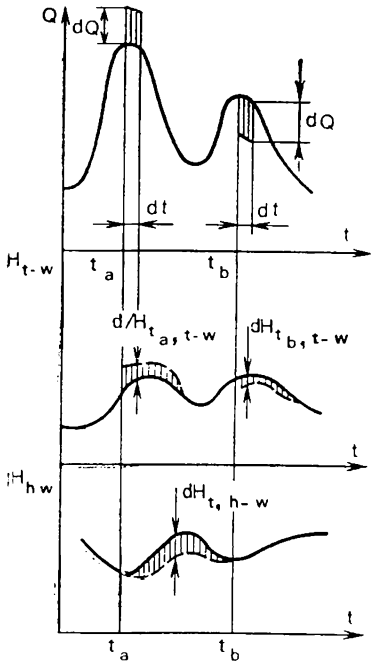


Fig. 6.7. Discharge vs head relationship

The thermal plant fuel economy

$$dB_a = dP_a b_a\, dt = b_a q_a^{-1} dQ\, dt = \lambda_a\, dV \quad (6.26)$$

where q_a, b_a = relative increments for HP and TPP

$\lambda_a = b_a q_a^{-1}$ = Lagrange multiplier

$dV = dQdt$ = additional run-off of the hydro plant

Equation (6.26) gives the fuel economy without allowance for the head variation. In actuality, an increase in the discharge rises the tail water level. Since this process attenuates slowly, it will last from t_a ad infinitum; the HP power will decrease by

$$dP_{a,\,t\text{-}w} = \frac{\partial P}{\partial H}\, dH_{t,\,t\text{-}w}$$

Thus, to estimate powers, one should know variation of the tail water level $dH_{t,\,t\text{-}w}$ which requires accounting of the non-stationary processes of the tail water. These methods are very complex and require labour-consuming calculations to obtain the values of $dH_{t,\,t\text{-}w}$, therefore, they are usually substituted by simplified procedures.

The additional fuel consumption at TPP, caused by the tail water level increase by $dH_{t,\,t\text{-}w}$,

$$dB_{a,\,t\text{-}w} = \int_{t_a}^{\infty} dP_{t,\,t\text{-}w} b_{a,\,t}\, dt = \Delta\lambda_{a,\,t\text{-}w}\, dV \quad (6.27)$$

where

$$\Delta\lambda_{a,\,t\text{-}w} = \frac{1}{\Delta V} \int_{t_a}^{\infty} dP_{t,\,t\text{-}w} b_{a,\,t}\, dt$$

This notation is introduced because the quantity $\Delta\lambda_{a,t\text{-}w}$ has the same dimension as the effectiveness coefficient λ of (6.24).

Applying the above to the moment t_b when the HP run-off balance is restored, we obtain

$$dB_b = \lambda_b\, dV \tag{6.28}$$

$$dB_{b,h\text{-}w} = \Delta\lambda_{b,t\text{-}w} dV \tag{6.29}$$

However, the head is also changed by variation of the head water, therefore the after-effect should be taken into account. During a period from t_a to t_b the hydro plant operates with the head water level reduced by $dH_{h\text{-}w}$ as compared with the initial conditions.

The reduction of the HP power at this period can be determined as

$$dP_{ab} = \frac{\partial P}{\partial H}\frac{\partial H}{\partial V} dV$$

the derivative $\frac{\partial P}{\partial H}$ showing variation of the HP power versus head, and $\frac{\partial H}{\partial V}$ head versus volume. In all the volume has been changed by dV. The excessive fuel consumption at TPP

$$dB_{ab} = \int_{t_a}^{t_b} dP_{ab} b_t\, dt = \Delta\lambda_{ab}\, dV \tag{6.30}$$

where

$$\Delta\lambda_{ab} = \int_{t_a}^{t_b} \frac{\partial P}{\partial H}\frac{\partial H}{\partial V} b_t\, dt$$

and it is readily apparent that the dimension of this quantity also coincides with that of λ of (6.24).

The overall change in the system fuel consumption on the basis of Eqs. (6.26)-(6.30)

$$dB_s = -dB_a + dB_{a,t\text{-}w} + dB_b - dB_{b,h\text{-}w} + dB_{ab} \tag{6.31}$$

If the initial distribution of load was better than the second variant, $dB_s > 0$; if the subsequent conditions are better, then $dB_s < 0$, i.e. fuel will be saved in the system. For further calculations assume that the conditions yield equal economy, which corresponds to $dB_s = 0$. Hence after cancellation of dV, we obtain

$$\lambda_b - \Delta\lambda_{b,t\text{-}w} = \lambda_a - \Delta\lambda_{a,t\text{-}w} - \Delta\lambda_{ab} \tag{6.32}$$

As follows from Eq. (6.32), when the HP head varies, the value of λ varies too rather than remaining constant as in the case of constant heads. Therefore, a particular effectiveness coefficient λ

should be determined for each time interval. As noted above, major difficulties are presented by the calculations of the tail water non-steady conditions. These difficulties may be overcome with the use of a computer and simplified calculation methods. It is precisely the calculation difficulties that often make the planner neglect the impact of the tail water and assume $\Delta\lambda_{a,t\text{-}w} = 0$ and $\Delta\lambda_{b,t\text{-}w} = 0$ even at the expense of accuracy of the entire problem. For daily optimization, the assumption of the head water invariance, i.e. $\Delta\lambda_{ab} = 0$, may be more frequently grounded.

On numerous occasions the difficulties of solving Eq. (6.32) stem from the lack of source information. For instance, it is impossible to calculate the non-steady conditions of the tail water or variations of the head water levels without the HP load schedules for the after-effect period. The history and current values of the HP power cannot ensure a sufficient accuracy of calculations. Therefore, in the real-time control of the hydro plant without a sufficiently reliable forecast of the HP loads for the forthcoming period, it is a common practice to assume that $\Delta\lambda_{a,t\text{-}w} = 0$, $\Delta\lambda_{b,t\text{-}w} = 0$, and $\Delta\lambda_{ab} = 0$. Additional optimization of the plan calculations is carried out on the basis of the current information over each discrete time interval.

6.4. Distribution of Load Between Power Plant Units

Using the Lagrange multiplier technique, it is possible to find the condition of optimal distribution of load between the units of a power plant. It implies that the ratio of the primary resource increment (power input) should be equal to the secondary increment (net power), the balance ratios being satisfied.

Distribution of load between units of thermal power plants. The distribution problem for TPP includes the subproblems of distributing load between the turbines, boilers, units and plant segments. The simple conditions for optimal distribution are found only with condensation turbine-generators, units and boilers.

The load optimal distribution conditions are as follows:

between condensing turbines

$$b_{T,i} = \frac{\Delta D_i}{\Delta P_i} = \text{idem} \tag{6.33}$$

where $b_{T,i}$ is the relative increment for the turbine which indicates variation of steam consumption ΔD_i when the turbine power is changed by ΔP_i;

between boilers

$$b_{B,i} = \frac{\Delta B_i}{\Delta D_i} = \text{idem} \tag{6.34}$$

where $b_{B,\,i}$ is the relative increment for the boiler which indicates variation in the consumption of the equivalent fuel of boiler ΔB_i when the steam production changes by ΔD_i;

between units

$$b_{U,\,i} = \frac{\Delta B_i}{\Delta P_i} = \text{idem} \tag{6.35}$$

where $b_{U,\,i}$ is the relative increment for the unit.

Hence

$$b_{U,\,i} = \frac{\Delta B_i}{\Delta P_i} = b_{T,\,i} b_{B,\,i} \tag{6.36}$$

The conditions of optimal distribution of load between the plant segments are similar to (6.33)-(6.36) but each segment is represented by the equivalent characteristic (equivalent characteristics of the turbines, boilers, segments of the plant).

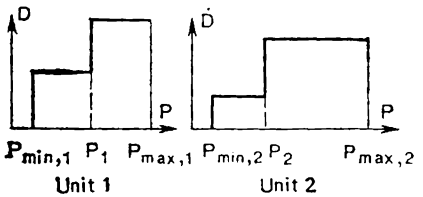


Fig. 6.8. To distribution of load with staircase characteristics of units

Actually, conditions (6.33)-(6.36) may be subject to constraints determined by the type of the unit characteristic. The characteristics may have abrupt changes, segments with constant relative increments, etc. All these peculiarities may be easily accounted for by the following simple regulations.

If the load is distributed between the turbines with staircase characteristics (Fig. 6.8), the units are loaded in the order of increasing relative increments. For instance when the load rises from minimum $P_{\min} = P_{\min,\,1} + P_{\min,\,2}$, first *unit 2* is loaded since it has the minimum relative increment. If the load exceeds $P_{\min} + P_2$, *unit 1* is loaded, then as the load exceeds $P_1 + P_2$, *unit 2* is loaded again and if it becomes greater than $P_1 + P_{\max,\,2}$, *unit 1*. This method satisfies the principle of using the units with a better fuel economy. The same technique is applicable to the units and boilers.

More difficult is to distribute load for the plants equipped with extraction turbines. Here the relative increments depend not only on the electric power but also on the amount of the steam extracted D_p. When distributing load between turbines with steam extraction, the optimality conditions take the following form:

$$\left.\begin{aligned} &q_{i,\,e} = \lambda_e \\ &q_{i,\,h} + \Delta q_{i,\,h}\beta_i = \lambda_h \\ &q_{i,\,p} + \frac{\Delta q_{i.\,p}}{\Delta D_{i,\,p}} D_{i,\,p} + \Delta q_{i,\,e}\alpha_i = \lambda_p \end{aligned}\right\} \tag{6.37}$$

where $q_{i,h}$, $q_{i,p}$ are the relative increments of heat consumption at changes in the amount of steam extracted for heating and processing and invariance of the electric power; $q_{i,e}$ is the relative increment of heat consumption at changes in the electric power; $\Delta q_{i,e}$, $\Delta q_{i,h}$, $\Delta q_{i,p}$, β_i, d_i are the values which can be found from the analytical notation of the turbine performance curve.

Distribution of load between units of hydro plants. The optimal distribution of load is achieved when the HP units operate with equal relative increments

$$q_i = \frac{\Delta Q_i}{\Delta P_i} = \text{idem}, \tag{6.38}$$

As proved by (6.33)-(6.38), if the relative increments of the units are known, optimal distribution of load between them is rather simple.

When distributing load between units in operation, it is preferable that the current measurements of the relative increments be used instead of characteristics. To determine the relative increment of a hydro plant unit, the discharge rates Q_1 and Q_2 and powers P_1 and P_2 should be measured at a small pitch

$$q \cong \frac{Q_2 - Q_1}{P_2 - P_1} \tag{6.39}$$

However, the differential index (6.39) is very sensitive to discharge and power measurement errors, can change abruptly if the processes are not stationary, it responds to various "irregularities" of the Q (P) curve, etc. Therefore, the measured characteristics of the relative increments are usually not convex, fail to meet the requirements of the Lagrange multiplier technique and offer low accuracy.

Figure 6.9 shows the curves of relative increments of units *1-3* for different hydro plants obtained in full-scale test. Before use these characteristics should be processed according to a special procedure. Low-quality characteristics diminish the effect of optimal distribution of load between the units. Determining high-quality field test characteristics of relative increments for thermal plants is also rather difficult.

Thus, the application of the relative increment method is restricted because of two reasons. Firstly, stringent requirements for the type of the unit characteristics necessitate their pre-calculations. The discharge and relative increment characteristics have to be stored in the computer memory which would involve tremendous preparatory work and increase the requisite memory capacity of the comp-

uter. Secondly, the differential indices (incremental rates) are very sensitive to variations of the absolute indices and change considerably as the units age, in the course of adjustment, etc.

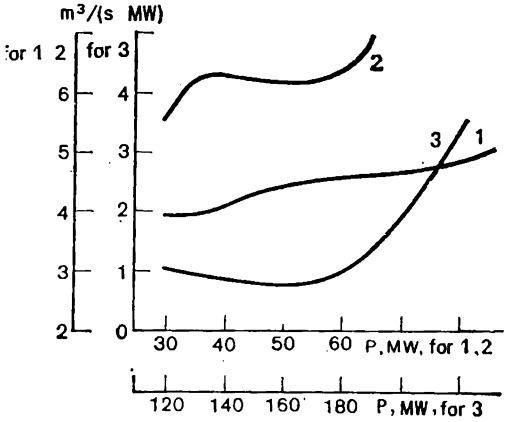


Fig. 6.9. Example of field-test characteristics of units
1-3—unit numbers

These factors cannot yet be taken into account in operation. Besides, the differential indices are not yet measured in actual practice.

6.5. Distribution of Load in Power System Comprising Nuclear Plant

Nuclear power plants become ever growing part of power system. Putting aside the entire complex of difficult problems involved in optimal operation of nuclear plants (NP), consider only those linked with optimal distribution of load in a power system comprising NP.

The NP energy production cost is

$$S_e = \frac{p_d C + E_o}{T_{max} P_{ins}} + \frac{E_l - E_{un}}{\eta_a Q_r T_c} \tag{6.40}$$

where C = capital costs of NP, roubles
E_o = operating expenses, roubles/year
p_d = depreciation rate
T_{max} = time of utilizing the NP installed capacity per annum, h/year
E_l, E_{un} = cost of nuclear fuel (loaded into and unloaded from nuclear reactor), roubles
T_c = duration of the cycle, h
Q_r = the thermal power of the reactor, kW
η_a = NP efficiency

The second term on the right of (6.40) is clearly the fuel component of the production cost. If the time of utilization of the installed capacity T_{max} increases (the base-load mode), the energy production cost is cut.

The energy characteristics of NP are determined by virtually constant losses in the reactor. The reactor losses are the dissipation ones. These are losses in the biological protection tank, primary piping heat dissipation from the steam generator surface and, finally, losses for blowing. The losses are slightly dependent on the energy load and amount to 0.25-0.5% of the total thermal power of the reactor.

Therefore, the incremental rate characteristic for the reactor steam generator system may be regarded as a constant for the reactors of all types. It is substantially independent from the load and equals $b_r = 0.0341$ t/GJ, while the consumption characteristic of the reactor is

$$B_r = B_{r,i} + b_r Q_r \tag{6.41}$$

where B_r, $B_{r,\,i}$ = consumption of equivalent fuel under load and at no-load respectively
Q_r = thermal power of the reactor

If NP is equipped with condensation turbines without overload valves, heat consumption in the turbine room

$$Q_{t\text{-}r} = \sum_{i=1}^{n} (Q_{i,\,i} + b_{T,\,i} P_{T,\,i}) \tag{6.42}$$

where $Q_{i,\,i}$ = no-load consumption of the ith turbine, GJ
$b_{T,\,i}$ = incremental rate of steam consumption, GJ/MW
$P_{T,\,i}$ = electric load of the turbine, MW

The total consumption of nuclear fuel is

$$B_r = B_{r,\,i} + 0.0341 \sum_{i=1}^{n} (Q_{i,\,i} + b_{T,\,i} P_{T,\,i}) \tag{6.43}$$

For similar turbines the incremental rate of nuclear fuel consumption for NP is found by the known rule of multiplying the rates, i.e.

$$b_{NP} = b_r b_T = 0.0341 b_T \tag{6.44}$$

Incremental rates of fuel consumption for typical turbines are given below:

Turbine power, MW	80	200	500
Incremental rate of steam consumption, GJ/(MW h)	13.39	10.55	10.04

Incremental rate of equivalent fuel consumption even for 150-MW units operating on solid fuel amounts to $b_{TPP} \approx 10.0$ GJ/(MW h)

which means that the thermal circuits of even very large NP units are thermodynamically less perfect than those of modern TPPs; therefore the nuclear plants will be optimally loaded only after 150-MW TPP units are loaded just as the 100-MW units. However, bearing in mind the fuel costs, NPs are well competitive with thermal power stations.

The condition of optimal distribution of load in a system comprising TPP, NP and HP is described by the following equations already known to us

$$\frac{c_{NP}b_{NP}}{1-\sigma_{NP}} = \frac{c_{TPP}b_{TPP}}{1-\sigma_{TPP}} = \frac{\lambda q}{1-\sigma_{HP}} = \text{idem} \tag{6.45}$$

The load distribution process is the same as in the case of two TPPs with different fuel costs.

6.6. Distribution of Reactive Loads

In practical calculations, the resistive and reactive loads are independently distributed among the plants of the system. The problem of distributing reactive loads can also be solved by the Lagrange multipliers technique. Inasmuch as the generation of the reactive power affects mainly the voltage and active and reactive power flows, the criterion of optimality is the active power losses. Minimizing the active power losses, we can decrease fuel consumption at the system plants. Write down the problem.

1. Objective equation—minimizing active power losses

$$\pi \Rightarrow \min \tag{6.46}$$

2. Coupling equation is $\pi_i (Q_i)$, where i is the number of the reactive power source.

3. Constraint equation is the balance equation of the reactive loads Q_l and powers Q_i of the reactive power sources, i.e.

$$W_Q = Q_l + \Delta Q - \sum_{i=1}^{r} Q_i = 0 \tag{6.47}$$

4. Optimization equation, when using the Lagrange multipliers, is

$$\frac{\frac{\partial \pi}{\partial Q_i}}{1-\frac{\partial (\Delta Q)}{\partial Q_i}} = \text{idem} \tag{6.48}$$

Derivation of the optimization equation. The Lagrange function comprises (6.46) and (6.47):

$$\Phi = \pi + \lambda W_Q = \pi + \lambda \left(Q_l + \Delta Q - \sum_{i=1}^{r} Q_i\right) \tag{6.49}$$

when the active-reactive power balance is observed.

The unknowns in this problem are r powers of the reactive power sources and the Lagrange multiplier λ, $r + 1$ unknowns in all. To solve the problem, set up r equations by differentiating the Lagrange function with respect to all independent variables and one balance equation (6.47).

Differentiating the Lagrange function, obtain r equations

$$\frac{\partial \Phi}{\partial Q_i} = \frac{\partial \pi}{\partial Q_i} - \lambda \left(1 - \frac{\partial \Delta Q}{\partial Q_i}\right) = 0 \tag{6.50}$$

From (6.50) it follows that

$$\lambda = \frac{\dfrac{\partial \pi}{\partial Q_1}}{1 - \dfrac{\partial \Delta Q}{\partial Q_1}} = \frac{\dfrac{\partial \pi}{\partial Q_r}}{1 - \dfrac{\partial \Delta Q}{\partial Q_r}} = \ldots = \text{idem} \tag{6.51}$$

which corresponds to (6.48).

This condition holds good when the reactive power generation is not linked directly with the fuel consumption or affects it but slightly. Otherwise, the problems of distribution of active and reactive powers should be solved together.

Condition (6.48) will be simplified when neglecting the reactive power losses, i.e. taking $\Delta Q = 0$; then the optimality condition takes the form

$$\lambda = \frac{\partial \pi}{\partial Q_i} = \text{idem} \tag{6.52}$$

Physical sense of condition (6.48). Write (6.48) in finite differences and multiply the numerator and denominator by ΔQ so that

$$\lambda = \frac{\dfrac{\Delta \pi}{\Delta Q} \Delta Q}{\left[1 - \dfrac{\Delta (\Delta Q)}{\Delta Q}\right] \Delta Q} = \frac{\Delta \pi}{\Delta Q - \Delta (\Delta Q)} = \frac{\Delta \pi}{\Delta Q_l} = \text{idem} \tag{6.53}$$

where ΔQ_l is the reactive power input at generation of power ΔQ.

From (6.53) it is seen that the optimal operation is ensured when the active power losses $\Delta \pi$ per unit reactive power input ΔQ_l are equal for all the sources of the reactive power.

6.7. Operation of Pumped-Storage Plants

The load schedules, especially for the European part of the USSR are becoming less busy today, while their peak-load fraction is growing. Alongside with the rise in load non-uniformity, the rise rate also increases. These factors anticipate the construction of pumped-storage plants (PSP). Several projects of large PSPs with a capacity of 1000-1500 MW have been developed for the integrated power systems of the Central, North-Western and Southern Areas of the USSR. Let us outline the operating conditions of PSPs.

The pumped-storage plants are similar to conventional hydro stations as regards the time of engaging the units from idling, load pick-up and shedding rate and other characteristics of the equipment operation. Change-over of the units from the pump mode to the turbine mode of operation requires approximately the same time as starting them from the idle state. To engage the pump mode somewhat longer time is needed since expelling of water from the impeller chamber might become necessary. The principal feature of the PSP operation is its pumping-generating cycle which is the main factor affecting its efficiency. The PSP efficiency is determined by the ratio of electric power generated during the generating cycle to that consumed during the pumping cycle. Today the efficiency amounts to 70-79%.

Operation of PSP in the pumping-generating cycle considerably affects the conditions of the entire power system. Actually, during pumping the reservoir is filled by consuming the energy of thermal power plants. Pumping is performed during off-peak periods. When the water is released to generate power, the thermal power stations of the system are unloaded.

The head, rate of discharge, electric power generation and consumption depend on the duration of the pumping and generating periods.

During PSP generating period, the upper reservoir is emptied while the lower one is filled, the head diminishes. During pumping, on the contrary, the upper reservoir is filled and the lower one is emptied; the head increases. These changes in the head are usually considerable so that the PSP optimization problem should be solved for the variable head.

Figure 6.10 illustrates variation of the PSP parameters at pumping and generating cycles.

When optimizing the PSP operation in the system, the period of calculation should be at least equal to the period of regulation. PSPs are as a rule subject to daily and weekly regulation but longer cycles are also possible.

The problem of optimal operation of PSPs has not yet been worked out in detail, whereas that of selecting the variables and condi-

tions of PSP operation in designing is more complete, however the designing problems are not covered by this book.

Using the same approach as for other optimization problems, construct a general mathematical model of optimal operation of PSP in the power system. The optimization objective is to determine

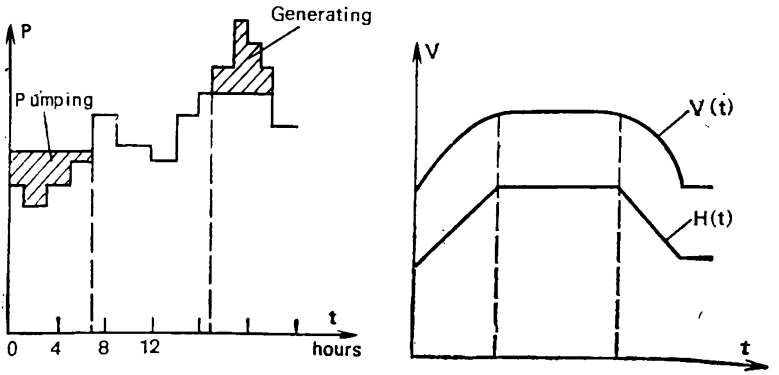


Fig. 6.10. Operation of pumped-storage plant

the conditions of utilizing the PSP energy during generation and accumulating it during pumping.

The problem is substantially similar to that of the mixed power system. For a system comprising k TPPs, p HPs and r PSPs, the mathematical model of the problem is as follows.

1. Objective equation

$$B = \sum_t B_t \Rightarrow \min \tag{6.54}$$

with $T \geqslant T_p + T_g$, where $T = \sum_j t_j$ is the total period of optimization, T_p and T_g are the pumping and generating periods of PSP.

2. Coupling equations

TPP characteristics $B_k(P_k)$;

HP characteristics $Q_p\ (P_p,\ H_p)$;

PSP characteristics for turbine mode $Q_{r,\,T}\ (P_{r,\,T},\ H_{r,\,T})$ and pump mode $Q_{r,\,P}\ (P_{r,\,P},\ H_{r,\,P})$.

3. Constraint equations

power balance equations

$$P_t - \left(\sum_k P_k + \sum_p P_p + \sum_r P_{r,\,T} - \sum_r P_{r,\,P} - \pi\right) = 0 \tag{6.55}$$

HP run-off balance equations

$$W_p = \sum_t W_{p,\,t} - W_{p,\,pr} = 0 \tag{6.56}$$

PSP run-off balance equation for pumping

$$W_{r,\,p} = \sum_t W_{r,\,t,\,p} \leqslant V \tag{6.57}$$

and generating

$$W_{r,\,g} = \sum_t W_{r,\,t,\,g} \leqslant V \tag{6.58}$$

where V = useful capacity of the upper reservoir;
constraint equation of the type

$$P_{\min} \leqslant P \leqslant P_{\max} \tag{6.59}$$

for all the stations.

4. The optimization equation set up for the Lagrange method of multipliers with the fixed-head HPs and variable-head PSPs will be

$$\frac{b_{h,\,t}}{1-\sigma_{h,\,t}} = \lambda_p \frac{q_{p,\,t}}{1-\sigma_{p,\,t}} = \lambda_{r,\,t} \frac{q_{r,\,t}}{1-\sigma_{r,\,t}} \tag{6.60}$$

The optimal operation is ensured when λ_p = const over all intervals $t = 1, 2, \ldots, n$ for each HP, provided the HP heads remain constant throughout the optimization period. The effectiveness coefficient for PSP does not remain constant and

$$\lambda_{r,\,t} = \lambda_{r,\,t-1} - \Delta\lambda_{(t-1),\,t} \tag{6.61}$$

where $\Delta\lambda_{(t-1),\,t}$ is the correction accounting for the after-effect stemming from changes in the upper reservoir conditions (see Sec. 6.3).

Since condition (6.60) is more complicated than (6.14), there is reason to believe that in the general case the Lagrange multipliers method alone can hardly provide an algorithm that would satisfy the convergence of the calculations. This problem is more likely to be solved with the use of a special algorithm incorporating a number of optimization techniques.

6.8. Complex Optimization of Power System Operation

In the general case the modern methods of non-linear programming have to be used for finding the solution. Let us consider the application of the reduced gradient method.

Any problem of the non-linear mathematical programming can be written in the following form. There is a function of many variables

$$F\,(Z,\,D) \tag{6.62}$$

Components Z are the operating conditions to be found and D incorporates the known source information on the system state,

then $\min F(Z, D)$ coincides with $\min F(Z)$. It is necessary to minimize, with respect to Z, the following function

$$F(Z) \Rightarrow \min \tag{6.63}$$

at constraints

$$W(Z) = 0 \tag{6.64}$$

$$Z_{\min} \leqslant Z \leqslant Z_{\max} \tag{6.65}$$

When using the reduced gradient method, the components of vector Z of the system operating conditions are divided into two subsets X and Y; Y comprises the independent variables, i.e. those which can be controlled by respective means of the system; X comprises the dependent variables, i.e. those which can be calculated from variable Y, then

$$Z(X, Y) = Z[X(Y), Y] \tag{6.66}$$

hence

$$\min F(Z) = \min F(X, Y) = \min F(Y) \tag{6.67}$$

whereas the constraints take the form

$$W(X, Y) = 0 \tag{6.68}$$

$$X_{\min} \leqslant X(Y) \leqslant X_{\max} \tag{6.69}$$

$$Y_{\min} \leqslant Y \leqslant Y_{\max} \tag{6.70}$$

The interrelations between independent variables Y and dependent variables X are usually implicit. Therefore, the function (6.67) is minimized by a multistep process.

The division of the operation variables Z into two subsets X and Y diminishes the dimension of the probem, hence facilitates calculations. Actually, if Z includes n variables and X, m variables, the problem dimension is generally $p \ll n$.

Consider the basic steps for solving the problem of complex optimization by the reduced gradient method for the all-thermal power system.

Statement of the problem. The integrated power system comprises $i = 1, 2, \ldots, M$ common and separate nodes and only three thermal power plants. The operation variables are as follows: $P_{G,i}$, $Q_{G,i}$ are the active and reactive powers of the generating nodes; V_i, δ_i are the voltage absolute values and phase angles in the system nodes. The nodal resistive and reactive loads are known; these are independent of system voltages or frequency. Find the optimal distribution of load for minimum consumption of the equivalent fuel in the system.

In this problem:

1. Objective equation

$$B(Z) \Rightarrow \min \tag{6.71}$$

The vector of variables Z is divided into the independent-variable vector

$$Y\ (V_i,\ \delta_i) \tag{6.72}$$

and the dependent-variable vector

$$X\ (P_{G,\,i},\ Q_{G,\,i}) \tag{6.73}$$

Then (6.71) can be written

$$B\ [V_i,\ \delta_i,\ P_{G,\,i}\ (V_i,\ \delta_i),\ Q_{G,\,i}\ (V_i,\ \delta_i)] \Rightarrow \min \tag{6.74}$$

2. The coupling equations include:

the equivalent characteristics of the generating nodes (power stations)

$$B_{i,\,e}\ (P_{G,\,i}) \tag{6.75}$$

where $B_{i,\,e}$ is the equivalent fuel consumption;

the interrelations between variables X and Y which are, as a rule, implicit and take the form of $Y\ (X)$;

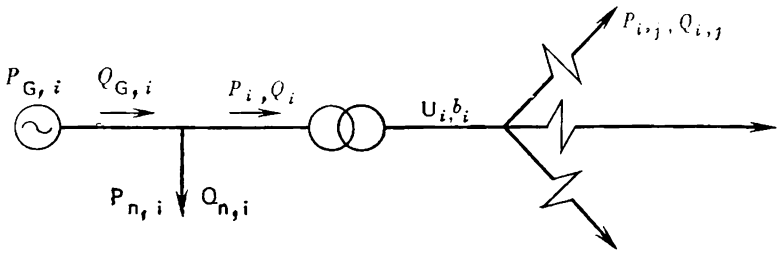


Fig. 6.11. Power system node

the constraint inequalities

$$P_{G,\,i,\,\min} \leqslant P_{G,\,i} \leqslant P_{G,\,i,\,\max} \tag{6.76}$$

$$Q_{G,\,i,\,\min} \leqslant Q_{G,\,i} \leqslant Q_{G,\,i,\,\max} \tag{6.77}$$

$$V_{i,\,\min} \leqslant V_i \leqslant V_{i,\,\max} \tag{6.78}$$

$$\delta_{i,\,\min} \leqslant \delta_i \leqslant \delta_{i,\,\max} \tag{6.79}$$

The active and reactive power balance constraints are introduced as a set of steady condition equations (Fig. 6.11).

The power unbalance for each node is

$$W_{P,\,i,\,u} = P_{i,u} = P_{G,\,i} - P_i - P_{n,\,i} \tag{6.80}$$

$$W_{Q,\,i,\,u} = Q_{i,u} = Q_{G,\,i} - Q_i - Q_{n,\,i} \tag{6.81}$$

where $W_{P,\,i,u}$, $W_{Q,\,i,\,u}$ are the unbalance function with respect to active and reactive powers.

When the system nodes are balanced under stationary conditions, $W_{P,\,i,\,u} = 0$, $W_{Q,\,i,\,u} = 0$. If independent variables V_i, δ_i are chan-

ged under stationary conditions, the unbalance will result and $W_{P,i,u} > > 0$, $W_{Q,i,u} > 0$. Changing $P_{G,i}$ and $Q_{G,i}$, we can determine new permissible stationary conditions for new values of V_i, δ_i. The task is to find such a solution of the steady condition equation whereat $B \Rightarrow \min$.

4. The optimal control equations are formed with the aid of the reduced gradient method. The solution is considered optimal if the absolute value of gradient-vector ∇B of the function $B(X, Y)$ is less than the given small value, i.e.

$$| \nabla B | \leqslant \varepsilon \tag{6.82}$$

The generalized flow chart of the algorithm is shown in Fig. 6.12.

Block 1. Assign any permissible values of Y_0 (V_i, δ_i) and calculate the system operating conditions, i.e. active and reactive powers of the generating nodes.

Block 2. Check constraints (6.76) and (6.77).

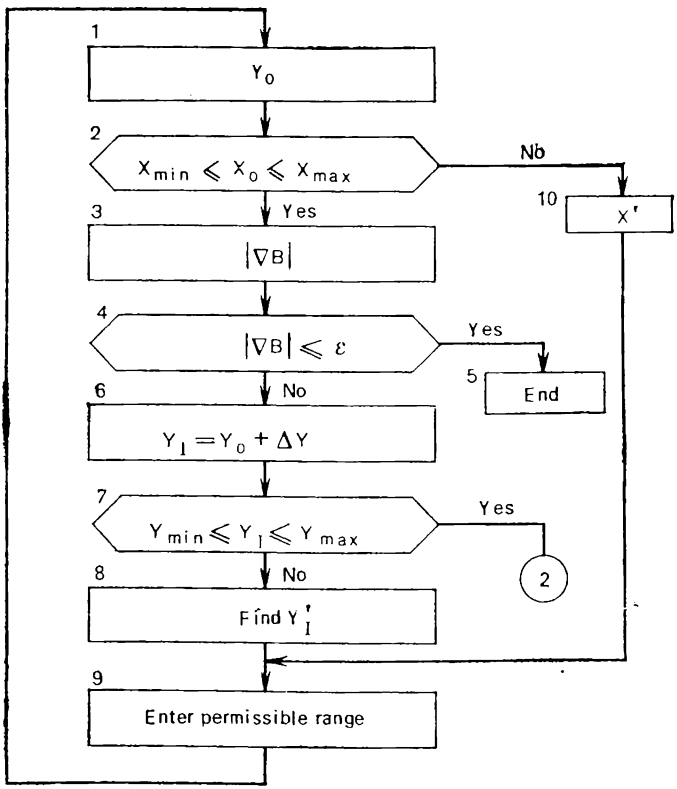


Fig. 6.12. Generalized flow chart of algorithm for complex optimization of system operation

If the powers are within the permissible limits, set up the optimization equation in block *3*. If the constraint is not satisfied or some powers are impermissible, they are set to their limit values and form the vector X' and the calculations are transferred to block *9*.

Block 3. The gradient of function $B\ (X,\ Y)$ in view of the implicit interrelation of variables $Y\ (X)$ takes the form

$$\nabla B = \frac{\partial B}{\partial Y} + \frac{\partial B}{\partial X}\frac{\partial X}{\partial Y} \tag{6.83}$$

Partial derivatives $\frac{\partial B}{\partial Y}$ and $\frac{\partial B}{\partial X}$ are found by differentiating equation (6.71) and (6.74), while partial derivatives $\frac{\partial X}{\partial Y}$, by differentiating equations (6.80) and (6.81) and

$$\frac{\partial X}{\partial Y} = -\left(\frac{\partial W}{\partial Y}\right)^{-1}\frac{\partial W}{\partial X} \tag{6.84}$$

Block 4. Determine the absolute value of the gradient vector and check its significance. If $|\nabla B| \leqslant \varepsilon$, the found values of Y_0 and X_0 are optimal and the calculations are completed (block *5*).

Block 6. If $|\nabla B| > \varepsilon$, the initial conditions, though permissible, are not optimal; in this case find the corrections for the independent variables and determine their new vector

$$Y_I = Y_0 + \Delta Y$$

The ΔY parameter variation step of this algorithm is calculated by the method of steepest descent which considerably speeds up the optimization process.

Block 7. Check that the new values of Y_I are permissible with respect to (6.76) and (6.77). If Y_I is beyond the permissible limits, solve the problem of bringing the conditions to the permissible range. To this end, fix the deviated variables at the boundaries of the permissible range and find a new vector of Y_I' (block *8*).

Block 9. To bring the conditions to the permissible range, the coordinates are changed. For obtaining stationary conditions, change any of variables X. One of the vector components, say X_i' is introduced into Y. Usually X_i' should exert the maximum effect upon variations of the unbalance function (6.80) and (6.81), i.e. for which

$$\max\left\{\left|\frac{\partial W_u}{\partial X_i'}\right|\right\} \tag{6.85}$$

where W_u is the unbalance function.

After the conditions are returned to the permissible range, restart optimization from block *3*.

The programs of calculations of the complex optimization problem which are based on the reduced gradient method offer a high ac-

curacy (the nodal power is balanced to 0.1 MVA) and for many occasions reasonable time. However, they are awkward, require large memory size and are therefore replaced for many practical applications with simpler algorithms and programs.

The complex optimization algorithm makes it possible to check at the real-time planning stage if the electric network voltage is permissible for different power consumption conditions (for a given load schedule). It may be used to select measures for maintaining the permissible conditions. Such measures include selection of voltage settings for automatic voltage regulation devices, transformer tapping, employment of synchronous condensers and capacitors, etc. This algorithm also allows one to perform check calculations at flow switchings.

When used jointly with the methods or algorithms for calculating the static or dynamic stability of the system, the complex optimization algorithm provides for determining the permissible power flows via different transmission lines, etc. However, the real-time control more frequently requires solution of separate problems so that the complex optimization algorithm need not be used.

6.9. Simplified Algorithm for Complex Optimization of Power System

The complex optimization problem resides in determining the optimal distribution of both the resistive and reactive loads in the system when the constraints comprise a sufficiently accurate and complete set of nonlinear equations derived from the set of Kirchhoff equations for the calculated electric circuit. It allows one to use a single algorithm for finding total powers of the stations and operating conditions of the electric system. The nodal voltages and phase angles are determined for the electric system, the active and reactive powers for all the branches of the system, and the transformation ratios for the transformers. With such a formulation the problem can be solved for the level of the power grid or integrated power system.

If the transmission line capacity constraint inequalities are neglected, the complex optimization problem can be solved by the Lagrange multiplier technique. Let us consider such a solution.

Let a power system comprise n active and m reactive power sources operating in parallel and connected to the load nodes by a network of an arbitrary configuration. The objective function remains

$$E = \sum_{i=1}^{n} B_i c_i \Rightarrow \min \tag{6.86}$$

However, in view of the power network losses the constraints change somewhat. The active power balance constraint is

$$\sum_{i=1}^{n} P_i - \pi - P = 0 \tag{6.87}$$

Likewise the reactive power constraint is

$$\sum_{i=1}^{m} Q_i - q - Q = 0 \tag{6.88}$$

Here π and q are active and reactive power losses in electric networks.

The Lagrange functional incorporates these two constraints and takes the form

$$\begin{aligned}\Phi = {} & [B_1 c_1 + B_2 c_2 + \ldots + B_n c_n] \\ & + \lambda_1 [P_1 + P_2 + P_3 + \ldots + P_n - \pi - P] \\ & + \lambda_2 [Q_1 + Q_2 + Q_3 + \ldots + Q_m - q - Q]\end{aligned} \tag{6.89}$$

The functional is minimum if

$$\left.\begin{aligned} & \frac{\partial B_i}{\partial P_i} c_i + \lambda_1 \left[1 - \frac{\partial \pi}{\partial P_i}\right] - \lambda_2 \frac{\partial q}{\partial P_i} = 0 \Big\} n \text{ equations} \\ & -\lambda_1 \frac{\partial \pi}{\partial Q_i} + \lambda_2 \left[1 - \frac{\partial q}{\partial Q_i}\right] = 0 \Big\} m \text{ equations} \end{aligned}\right\} \tag{6.90}$$

We derived the formulas on the assumption that the active and reactive power losses in the network depend on the resistive and reactive loads of the power plants.

Find the ratio λ_2/λ_1 from the equations of the second group of (6.90)

$$\frac{\lambda_2}{\lambda_1} = \frac{\partial \pi / \partial Q_i}{1 - \partial q / \partial Q_i} \tag{6.91}$$

Designate $\lambda_2/\lambda_1 = J$ and $\partial q_i/\partial Q_i = \sigma_{Q,\,i}$, where σ_Q is the differential index (relative increment) of reactive power losses in the network. It illustrates how the reactive power losses increase in the entire network when the reactive load of the ith source is changed by a unit. Now

$$J_i = \frac{\partial \pi / \partial Q_i}{1 - \sigma_{Q,\,i}} \tag{6.92}$$

Writing this equation for each of m reactive power sources and equating the right-hand sides of (6.92), we obtain the condition of optimal distribution of the reactive powers of the system in the form of equal ratios

$$\frac{\partial \pi / \partial Q_i}{1 - \sigma_{Q,\,i}} = \text{idem} \tag{6.93}$$

Let us now focus our attention on the equations of the first group in (6.90). Write one of them as

$$b_i c_i + \lambda_1 [1 - \sigma_i] - \lambda_1 J_i \frac{\partial q}{\partial P_i} = 0 \tag{6.94}$$

$$\sigma_i = \partial \pi / \partial P_i \tag{6.95}$$

where σ_i is the differential index (incremental rate) of active power losses in the system, illustrating how the active power losses increase in the entire network when the active load of the ith station is changed by a power increment unit (e.g. by 1 MW).

Solve Eq. (6.94) for λ_1

$$-\lambda_1 = \frac{b_i c_i}{1 - \sigma_i - J_i \partial q / \partial P_i} \tag{6.96}$$

Substituting the value of J_i from (6.92) into (6.96) and repeating this step for all the equations, we obtain

$$\frac{b_i c_i (1 - \sigma_{Q,i})}{1 - \sigma_i - \sigma_{Q,i} + \sigma_i \sigma_{Q,i} - \dfrac{\partial q}{\partial P_i} \dfrac{\partial \pi}{\partial Q_i}} = \text{idem} \tag{6.97}$$

This is the general condition of optimal distribution of resistive and reactive loads making allowance for network power losses in a complex power system.

If the active and reactive powers are distributed independently of each other, this condition is divided into two

$$\left.\begin{aligned} \frac{b_i c_i}{1 - \sigma_i} &= \text{idem} \\ \frac{\partial q / \partial P_i}{1 - \sigma_{Q,i}} &= \text{idem} \end{aligned}\right\} \tag{6.98}$$

It may be proved that in case of a uniform electric network, i.e the network all the elements of which have a constant specific resistance-to-reactance ratio $\frac{r_0}{X_0} = \text{const}$, the general condition of optimal load distribution is simplified. For such networks the condition

$$\frac{\partial q}{\partial P_i} \frac{\partial \pi}{\partial Q_i} = \frac{\partial \pi}{\partial P_i} \frac{\partial q}{\partial Q_i} = \sigma_i \sigma_{Q,i} \tag{6.99}$$

is satisfied.

The condition of optimal distribution of load in uniform networks is

$$\frac{b c_i (1 - \sigma_Q)}{1 - \sigma_i - \sigma_{Q,i}} = \text{idem} \tag{6.100}$$

Dwell on calculations of the network loss derivatives. In the general case, we should find four derivatives: σ, σ_Q, $\partial q/\partial P_i$ and $\partial \pi/\partial Q_i$. This is a challenging task. The derivative versus station load relationship is not linear. Besides, the loss derivative depends not only on the total load of the system but also on the load distribution between separate nodes.

Consider a uniform network which is the simplest case. Network losses are

$$\pi = \sum_{s=1}^{l} \frac{P_s^2 + Q_s^2}{V_s^2} r_s \tag{6.101}$$

where l = number of lines
r = line resistance
V = voltage
$P_s + jQ_s$ = resistive and reactive loads of the line

In the uniform network, the resistive loads are independent of the reactive ones, therefore

$$\sigma_i = \frac{\partial \pi}{\partial P_i} = \frac{2}{V^2} \sum_{s=1}^{l} P_s r \frac{\partial P_s}{\partial P_i} \tag{6.102}$$

where $P_s r$ = voltage loss from node s to the balancing node, it is equal in all the parallel branches
$\frac{\partial P_s}{\partial P_i}$ = coefficient of power flow distribution

The sum of the coefficients of all the branches is equal to unity. Finally,

$$\sigma_i = \frac{2}{V_n^2} P_s r_s \tag{6.103}$$

Now discuss loss derivatives in the non-uniform network.

The network active power losses can be written as nodal loads

$$\pi = \sum_{i=1}^{n-1} \sum_{g=1}^{n-1} [B_{i,g}(P_i P_g + Q_i Q_g) - C_{i,g}(P_i Q_g - P_g Q_i)] \tag{6.104}$$

The reactive power losses are

$$q = \sum_{i=1}^{n-1} \sum_{g=1}^{n-1} [D_{i,g}(P_i P_g + Q_i Q_g) + F_{i,g}(P_i Q_g - P_g Q_i)] \tag{6.105}$$

where i and g are the node numbers; P and Q are the nodal resistive and reactive loads; $B_{i,g}$, $C_{i,g}$, $D_{i,g}$ and $F_{i,g}$ are the loss factors. They are as follows

$$\left.\begin{aligned} B_{i,g} &= B_{g,i} = \frac{r_{i,g}\cos\theta_{i,g}}{V_i V_g} \\ C_{i,g} &= \frac{r_{i,g}\sin\theta_{i,g}}{V_i V_g} = -C_{g,i} \\ D_{g,i} &= D_{i,g} = \frac{x_{i,g}\cos\theta_{i,g}}{V_i V_g} \\ F_{i,g} &= \frac{x_{i,g}\sin\theta_{i,g}}{V_i V_g} = -F_{g,i} \end{aligned}\right\} \qquad (6.106)$$

Here $r_{i,g}$ and $x_{i,g}$ are the resistance and reactance of the line connecting nodes i and g with voltages V_i and V_g; $\theta_{i,g}$ is the vector shift angle at the ends of the line.

Variation of any of nodal powers changes the absolute values and angles of voltages in all the nodes except the balancing one. This complicates calculation of derivatives. Usually the absolute values and angles are assumed constant, then differentiating the equations with respect to the corresponding loads, we obtain

$$\left.\begin{aligned} \sigma_i &= 2\sum_{g=1}^{n-1} P_g B_{i,g} - 2\sum_{\substack{g=1 \\ i\neq g}}^{n-1} Q_{g,i} C_{i,g} \\ \frac{\partial\pi}{\partial Q_i} &= 2\sum_{g=1}^{n-1} Q_g B_{i,g} + 2\sum_{\substack{g=1 \\ i\neq g}}^{n-1} P_{g,i} C_{i,g} \\ \frac{\partial q}{\partial P_i} &= 2\sum_{g=1}^{n-1} P_g D_{i,g} - 2\sum_{\substack{g=1 \\ i\neq g}}^{n-1} Q_{g,i} F_{i,g} \\ \sigma_{Q,i} &= 2\sum_{g=1}^{n-1} Q_g D_{i,g} + 2\sum_{\substack{g=1 \\ i\neq g}}^{n-1} P_g F_{i,g} \end{aligned}\right\} \qquad (6.107)$$

6.10. Realization of Calculations for Optimal Distribution of Load of Power Plants and Systems

The previous sections discussed mathematical models for modifications of the problem of optimal distribution of load. These models are used to construct algorithms and computer programs, however their realization is rather a challenging task. We can accurately compute the optimal operating conditions but to obtain the desired results the solution should be realized quickly and exactly. According to the temporal hierarchy of the power industry manage-

ment, there are two levels of solving the problem of load optimal distribution.

The computer programs are used today for the overwhelming majority of calculations in the current and short-term planning. Such programs are elaborated for pools, systems, and stations and the computers are used in the adviser mode.

There are also specialized analog computers which allow one to solve a number of optimization problems. However, they have not found wide application and are being ousted by the digital computers. The basic shortcoming of the analog computers is that they cannot ensure a sufficiently accurate representation of the electric circuit of the system, complex circuits of thermal power plants, individual characteristics of multi-unit hydro stations, etc.

Modern programs offer different accuracy and time of calculation, accounting for the system status information to a different degree of completeness. The best-suited program can be chosen by analyzing the particular operating conditions.

To realize the optimal distribution of load in the real-time control, use is made of dispatch facilities, special automatic equipment and specialized analog and general-purpose computers incorporated in APCS.

Group control of power plant units. The power plants are provided with automatic active and reactive power group control (APGC and RPGC) devices. All the units incorporated in the group control are considered as entity. The control of the unit is effected with a simultaneous maintenance of a particular parameter of the station at the desired level.

The APGC system automatically distributes the resistive load of the plant between the units. The distribution may be either uniform or with constant coefficients. The APGC system also regulates the plant load. The plant load is usually regulated with respect to the system frequency. At HPs the regulation may be effected with respect to the discharge rate and water levels. If the regulation law does not account for load variation, the load distribution between the units cannot be optimal when the load of the plant changes.

Computerization of APGC opens up new possibilities. At the initial stage, special computing devices (SCD) were developed to find optimal or near-optimal coefficients of load distribution. These coefficients were transmitted to APGC. The special computing devices determined the optimal conditions from the equation of the unit incremental rates. A schematic diagram of such a device is shown in Fig. 6.13. It can solve equations of the type

$$b_1 = b_2 = \ldots = b_n = \mu$$
$$P_1 + P_2 + \ldots + P_n = P_\Sigma$$

where each unit is simulated by its characteristic of incremental rates b (P). The load setter (LS) supplies plant loads P_Σ and the computer selects such a coefficient μ whereat the total power of the units gives P_Σ. Powers P_1, P_2, . . . determined by the computer will be set at the units through APGC.

Still stronger possibilities are offered when combining APGC with a general-purpose computer within APCS, which is provided for, e.g. in HP APCS. Optimal loads of units with due regard for various operation and performance constraints are programmed. APGC adjusts the distribution opening and power of the turbine via its speed governor. The potentialities of the second variant are greater since the general-purpose computer handles a plurality of different problems rather than solving this only task. For instance, it distributes the reactive powers between the units. The RPGC system realizes the load distribution found by the computer. The required reactive powers of the units are set by the generator field controllers. The reactive load distribution can be both uniform and non-uniform.

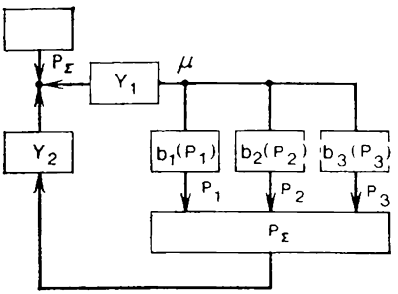


Fig. 6.13. Special computing device for distributing load between units

Automatic devices ensure realization of the optimal operating conditions accurate to 1-2%. In APCS this accuracy is improved and is determined by the precision of the sensors.

Individual control of plant units. The operating conditions of a unit controlled individually are determined by the dispatcher who uses the dispatch control means (switches, buttons, etc.). The dispatcher follows the recommendations for distributing station load between the units, which are elaborated when compiling current schedules with the aid of a computer or directly from the latter in the real-time mode within the framework of APCS. The optimality condition is checked against the instruments on the panel. The accuracy of the panel instruments used to measure power, voltage, and frequency dictates the precision of realization. The realization error usually does not exceed 2-5%.

Distribution of load between power plants of system. The optimal distribution of resistive and reactive loads between the power plants is carried out and supervised by the system dispatcher. Using recommendations obtained in computerized real-time planning, the dispatcher transmits the resistive and sometimes reactive load curves, voltage control graphs and other necessary information to the power

plants. Checking system performance and parameters, the dispatcher estimates matching of the forecasted (planned) and actual operating conditions of the system. If there is a mismatch, he introduces corrections to the plant schedules. With the automated dispatch control system (ADCS) the corrections are introduced using a computer.

The plan-correction principle is more advantageously embodied in the power system MCSs. Automated acquisition, quick and positive processing of the system status data are possible only within

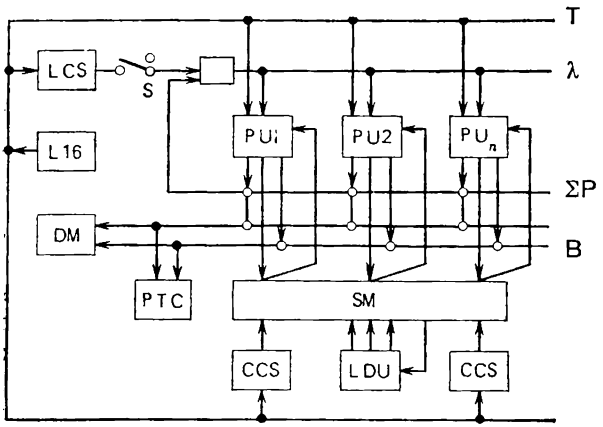


Fig. 6.14. Functional diagram of device for distributing load between units

the framework of MCS. Otherwise, the dispatcher updates the conditions using only his knowledge, intuition and instrument readings, which of course decreases the efficiency of control.

SCDs are also developed for distributing load between stations but their employment is restricted. One of such devices EKPAN-7 realizes the conditions

$$\frac{b_i}{1-\sigma_i} = \frac{\lambda_j q_j}{1-\sigma_j}$$

$$\sum_k P_k + \sum_i P_i + \sum_j P_j - \pi = P_\Sigma$$

where i is the number of TPP, j is the number of HP, k is the number of inter-system connections.

Figure 6.14 shows a functional diagram of the device. The load of the system may be set either through the load curve setter (LCS) or manually by switch S. The characteristics of incremental rates for the plants are modeled in the plant units (PU). The system model (SM) unit embodies a dc model and provides for obtaining incremental rates of losses σ_i, σ_j. The communication curve setters

(*CCSs*) set the schedules of power transfers along the connection lines from the adjacent systems. Digital meter (*DM*) allows one to determine the fuel consumption and water discharge rates. The circuit operates as follows. The calculated daily load curves are set in *LCSs* and *CCSs*. The total load is also set for each node of the system with the aid of the load distribution unit (*LDU*). Power of each station P and sum of powers ΣP are determined at the outputs from *PUs* for a particular value of λ. The system model unit finds σ_j, σ_i for known P and corrects the load distribution using the feedback principle. The coefficient λ should be so selected as to satisfy the balance condition. The characteristics of *PUs* may change with time t.

The EKRAN-7 device employs semiconductors and is fairly reliable. It gives, however, only an approximate solution because of a considerable equating of the electric network in unit *SM*, approximate methods of network analysis, etc.

Frequency and active power automatic control system. Frequency control is known to be linked with active power regulation. The rated frequency is maintained by changing powers of units and stations, hence involves distribution of load in the system. Consumer load variations are not amenable to precise measurements even over short intervals of time so that frequency variations are persistent. Frequency primary control is a function of the turbine speed governors and steadiness of their behaviour dictates distribution of load between the units. We remember that only APCS makes it possible to systematically adjust the constant-error behaviour. Since the primary control usually cannot alone maintain the desired frequency in the system, secondary control is resorted to. Secondary control is accomplished either automatically or manually and allows one to shift the speed governor characteristics till the rated frequency is set. As a rule only some plants of the system utilize secondary control of frequency so that the load can be redistributed only between these particular stations.

The capacity of the inter-system tie lines is of great significance in frequency control of integrated power systems. When frequency is controlled, the tie line load changes and may reach the maximum permissible values. To preclude over-loading of the inter-system tie lines, the power transfer schedules are compiled. One of the systems of the pool is assigned to control frequency, while all other systems maintain the required power transfers. This affects the load distribution in the pool.

It is impossible to recognize all the particulars of frequency control in the optimal load distribution algorithms, however some of them are accounted for in the automatic frequency control devices. For instance, the powers found at optimization may be periodically assigned during automatic frequency control (AFC) so that the

unit power fluctuates around the optimal value. The new power values should be input in the AFC system after approximately 15-20 min, the time being determined either by the frequency deviation from the rated limit or by the electric time error.

The optimal distribution of load gains still greater importance in the automatic frequency and active power control (AFAPC) of the pool. The load is distributed between the units according to their incremental rate characteristics (IRC). Provision is also made for manual correction of IRCs. The incremental rate characteristics of the power plants are determined by summing up IRCs of separate units. Load distribution between the stations is effected with due regard for network power losses.

7

CHARACTERISTICS OF POWER PLANTS

7.1. Energy Characteristics of Equipment

The principal problems linked with operating conditions use characteristics of absolute, relative and differential indices of the equipment.

Main *absolute indices* are the useful (net) power P; the power input P_i and the energy resource consumption (fuel B, water Q, steam D, heat Q_{TPP}). Obviously the power input is directly proportional to the energy resource consumption. For instance, in case of a fixed-head hydro plant, $H = \text{const}$, the power input

$$P_{i,\,HP} = 9.81HQ \equiv Q \tag{7.1}$$

For TPP the power input, MW, is proportional to the equivalent fuel consumption

$$P_{i,\,TPP} = 8.14B \equiv B \tag{7.2}$$

Main *relative indices* are the efficiency η and the specific consumption of energy resource b_{sp}. It is known that the efficiency

$$\eta = P/P_i \tag{7.3}$$

and the specific consumption is a reverse, i.e.

$$b_{sp} = P_i/P \tag{7.4}$$

In case of TPP, we shall use symbol b_{sp}, for HP, q_{sp}.

Of the *differential indices*, the most widely used are the so-called incremental rates illustrating changes in the power input at variations of the useful power, i.e.

$$b = \Delta P_i/\Delta P \tag{7.5}$$

Specific and differential indices for different types of the energy equipment are designated by different symbols.

The absolute, relative and differential indices are used to plot the energy characteristics of units and stations. Let us discuss the main ones in brief.

Consumption characteristics of units: $P_i(P)$, $B(P)$, $Q(P)$, etc. are usually curves with a shallow downward convexity (Fig. 7.1, curve *1*). However, the monotony of the curve may be disrupted with jumps. On the steam turbine curves the jumps stem from the throttling

action of the control valves (curve *2*, Fig. 7.5), on the hydro unit curves $Q(P)$ from cavitation.

Operating characteristics: $\eta(P)$, $\eta(P_i)$, $\eta(B)$, $\eta(Q)$, etc.

The efficiency is usually represented by a single-extremum curve. Very seldom the curves of Kaplan turbines of HPs may have a second extremum (Fig. 7.2, dashed line).

Specific characteristics: $q_{sp}(P)$, $b_{sp}(P)$ ($q_{sp} = Q/P$, $b_{sp} = B/P$). Curve b_{sp} is shown in Fig. 7.2. Usually the characteristic takes the

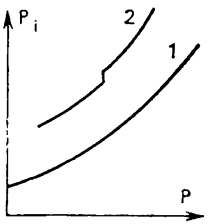


Fig. 7.1. Consumption characteristics of units
(*1*) convex; (*2*) with discontinuity

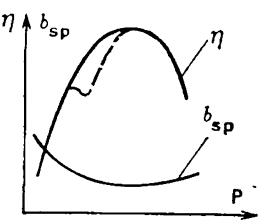


Fig. 7.2. Unit characteristics in terms of relative indices

form of a function with one extremum. Of particular interest is the minimum point of the energy resource specific consumption which corresponds to a load whereat the efficiency is maximum.

Differential characteristics: $q(P)$, $b(P)$, etc. ($q = \Delta Q/\Delta P$, $b = \Delta B/\Delta P$). These are also called characteristics of incremental rates. The simplest way of plotting them is the tabular differentiation of the consumption characteristics. We shall not discuss here the differentiation technique. If the differential index is found from (7.5), it becomes dimensionless allowing one to compare differential indices of various objects (thermal, mechanical, electrical).

Characteristics of TPP units. The power unit comprises a boiler, a turbine, a generator and is therefore described in terms of their characteristics (Fig. 7.3). The energy characteristic of a boiler shows the interrelation between the hourly consumption of equivalent fuel B, t/h, and the boiler steam generating capacity D, t/h. The latter is measured by the hourly consumption of steam with rated parameters (Fig. 7.4*a*). Using such a characteristic, one should bear in mind that the fuel consumption B depends not only on the steam consumption D but on some other parameters of the boiler (steam pressure and temperature, cooling water temperature, feedwater temperature, vacuum created in the condenser, etc.). These parameters cannot remain constant throughout the boiler operation; therefore, representing the power unit characteristic as a function of one variable (generator active power P) is a fairly

rough approximation. A more reasonable way is to pick up a group of the leading parameters and correct (recalculate) the energy characteristic to the actual (or forecasted for the near future) value

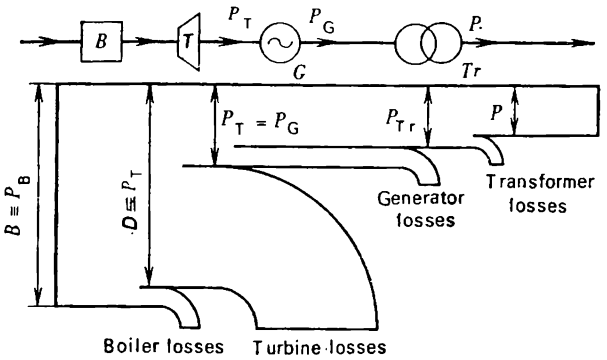


Fig. 7.3. TPP unit operation losses

of the unit parameters. Such an approach is being implemented in APCS of electric stations. Differentiating the consumption characteristic of the boiler with respect to its steam generating capacity, we obtain the differential characteristic of the boiler. It gives the incremental rate of fuel consumption versus steam generating capacity

$$b_h = \partial B/\partial D$$

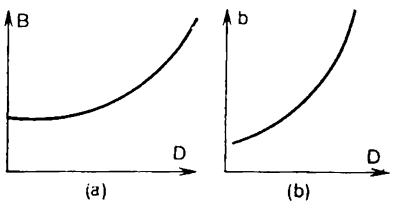


Fig. 7.4. TPP boiler characteristics
(*a*) consumption; (*b*) differential

On most occasions the differential characteristic of a boiler is a monotonically rising curve (Fig. 7.4*b*).

The energy characteristic of a turbine shows the consumption of steam with rated parameters versus turbine power P_T. It is a straight (*1*) or broken (*2*) line in Fig. 7.5. The inflection point corresponds to engagement of the overload valve for boosting the turbine power.

The differential characteristic of a turbine represents the dependence of $b_T = \dfrac{\partial D}{\partial P_T}$ on the turbine power P_T. It is a horizontal straight line *1* or two horizontal segments *2* (Fig. 7.6).

The energy characteristic of a generator (Fig. 7.7*a*) indicates the dependence of the active power across the generator terminals on the turbine power and reactive load of the generator, i.e. $P_G = f(P_T, \cos\varphi)$. The differential characteristic of a generator

(Fig. 7.7*b*) illustrates the dependence of the turbine specific power increment on the load increment at the generator terminals $b_G = \frac{\partial P_T}{\partial P_G}$ as a function of resistive and reactive loads of the generator.

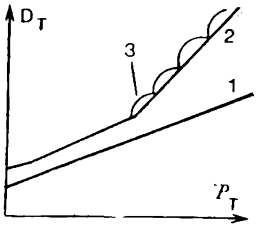


Fig. 7.5. TPP turbine consumption characteristics
(*1*) without inflection point; (*2*) with inflection point; (*3*) deflection at incomplete opening of regulating valves

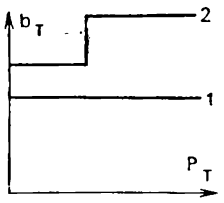


Fig. 7.6. TPP turbine differential characteristics
(*1*) without inflection point; (*2*) with inflection point

The value of P_T may be represented in terms of the generator efficiency η_G. Since $P_T = P_G\eta_G$,

$$b_G = \frac{\partial (P_G\eta_G)}{\partial P_G} = \eta_G + \frac{\partial \eta_G}{\partial P_G} P_G \qquad (7.6)$$

Thus, to calculate b_G, we may differentiate the operating characteristic of the unit.

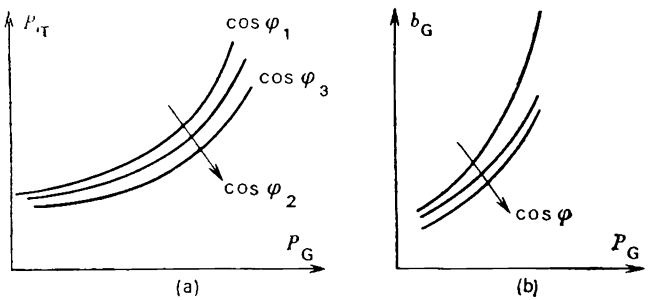


Fig. 7.7. Generator characteristics
(*a*) in absolute indices; (*b*) differential

The product of the differential indices of the boiler, turbine and generator is a differential index of the entire unit

$$b_{unit} = b_B b_T b_G \cong \frac{\Delta B}{\Delta D} \frac{\Delta D}{\Delta P_T} \frac{P_T}{\Delta P_G} = \frac{\Delta B}{\Delta P_G} \qquad (7.7)$$

The differential characteristic of the unit may take different forms depending on whether the unit has or has not an overload

region (Fig. 7.8). Accounting for the unit axiliary power adds jumps stemming from cut-in of largest house consumers, such as feed pumps, smoke exhausters, etc.

The characteristics of a turbine-generator set may be represented as a finite number of convex segments with a jump between them.

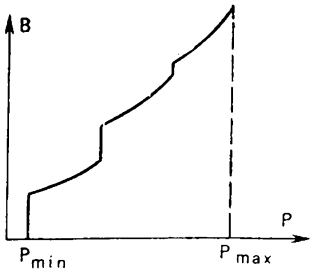


Fig. 7.8. TPP unit consumption characteristic

Differential characteristics of nuclear plants. These include incremental rates for the reactor, turbine and generator

$$b_{NP} = b_R b_T b_G \qquad (7.8)$$

Differential index b_R does not depend on the reactor loading (Sec. 6.5); therefore, b_{NP} is almost entirely determined by the differential index of the turbine. The energy performance of the NP turbines is inferior to that of the hydro turbine of the same power because of lower parameters of the steam (temperature, pressure).

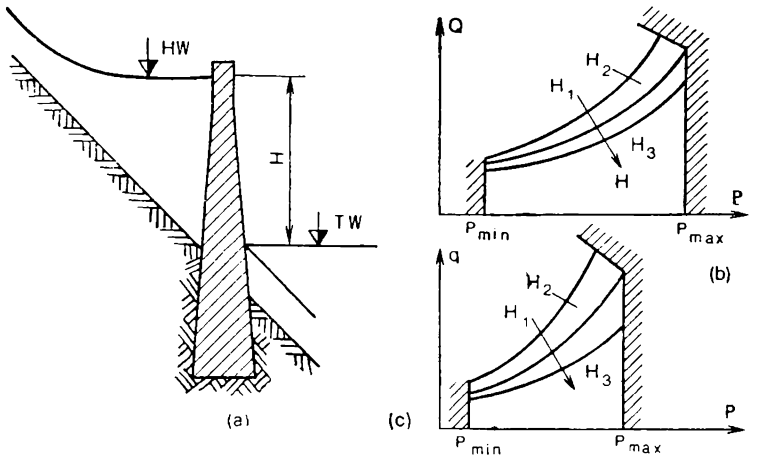


Fig. 7.9. HP unit characteristics
(*a*) installation diagram; (*b*) discharge; (*c*) differential

Characteristics of hydroelectric units. These are usually depicted as fixed-head isolines (Fig. 7.9). For instance, isolines $Q(P)$ for $H = \text{const}$ are traced on the consumption characteristic (Fig. 7.9*b*), isolines $q = \partial Q/\partial P$ on the differential characteristic (Fig. 7.9*c*).

7.2. Slewability of Thermal Power Plants

Thermal power plants participate in frequency control and power flow regulation, and in power emergency control. The degree of such a participation depends on slewability of the TPP equipment and automatics. The slewability is determined by the range of permissible loads (load range) and control range.

If $P_{j,\min}$ and $P_{j,rtd}$ are respectively the permissible minimum and rated loads of the jth unit, the *load range*, %, is

$$d_{l,j} = \frac{P_{j,rtd} - P_{j,\min}}{P_{j,rtd}} 100 \qquad (7.9)$$

Within this range it is possible to change the composition of the auxiliary equipment and disconnect separate automatic controllers. For a particular unit whose rated power is known the load range may be single-valuedly determined by the relative value of the minimum permissible continuous power $P^*_{j,\min}$

$$d_{l,j} = \left(1 - \frac{P_{j,\min}}{P_{j,rtd}}\right) 100 = (1 - P^*_{j,\min}) 100 \qquad (7.10)$$

Control range is the range within which the loads can be adjusted automatically without the need for changing the set of the primary and auxiliary equipment or burners. The process automatic controllers should ensure troublefree operation at any loads within the con-

Table 7.1

Minimum Permissible Loads of 160-, 200- and 300-MW Single-Boiler Single-Turbine Units

Power, MW	Boiler type	Fuel	Slag removal	Minimum load, %
160	ТП-90	АШ coal	Liquid	70
160	ТП-92	Gas	—	40
160	ТГМ-94	Gas, fuel oil	—	40
200	ПК-33	Chelyabinsk brown coal	Dry	50
200	ТП-100	АШ coal	Liquid	70
		Ditto	Ditto	60*
		Donetsk coal	Ditto	60
		Ditto	Ditto	50*
		Lvov-Volyn coal	Dry	65
			Liquid	40*
300	ТП-110	АШ Kuznetsk coal	Ditto	70
		Ditto	Ditto	60*
	ТГМП-314	Gas, fuel oil	—	30

* Operation period up to 2 h.

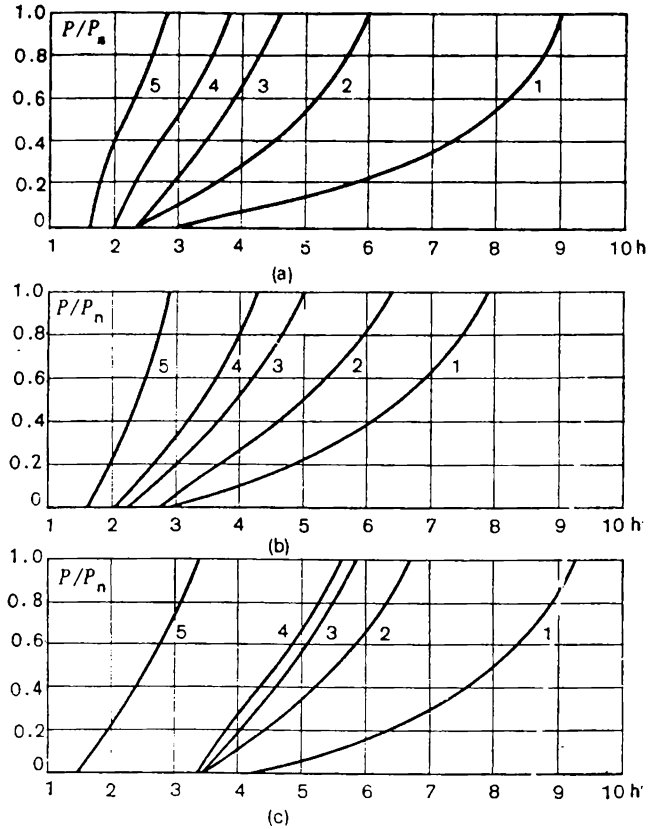


Fig. 7.10. Characteristics of rated maximum duration of starting periods for single-boiler single-turbine units with pulverized-coal boilers

(*a*) 160-MW unit; (*b*) 200-MW unit; (*c*) 300-MW unit; *1*—start from cold; *2*—ditto 50-60 h after starting (time t is counted from starting boiler); *3*—ditto after 20-35 h; *4*—ditto after 15-20 h; *5*—ditto after 6-10 h

trol range. If necessary, the controller settings can be automatically changed to ensure automatic regulation inside the entire load range (adaptive control systems).

For units operating on fuel oil and gas the permissible load range should be at least 50%, on coal with dry slag removal 40%, with liquid slag removal 20%, i.e. $P^*_{\min}$ is equal to 50, 60 and 80%, respectively. Some data on minimum permissible loads of separate single-boiler single-turbine units with a power up to 300 MW are presented in Table 7.1.

Another important characteristic of unit slewability is the *start duration*. For single-boiler single-turbine units of 160, 200 and 300 MW operating on pulverized coal, these characteristics are shown in Fig. 7.10. As seen from the figure, start duration t depends greatly

upon the unit outage (cooling) period and to a lesser extent upon the power and type of the unit. The cold unit can be started in 8-9 h of which 5-6 h are spent for loading. After the minimum outage (6-10 h) the unit starting requires 3 h about a half of which is used for loading.

Calculation of fuel consumption for unit starting. For training purposes the data of Table 7.2 can be used.

Table 7.2

Equivalent Fuel Consumption for Starting Units of Condensation Power Plants, t

Unit status	Unit power, MW			
	100	160	200	300
Cold	30	50	60	150
After outage				
24-h	21	40	60	100
8-10-h	8	25	30	80

It is regarded that at short outage periods (up to 16-18 h for most of the units), the starting consumptions are proportional to the outage time

$$B_{out} = b_{out}T \tag{7.11}$$

where b_{out} is the constant factor determined by the specifications of the equipment.

In case of a long-term outage, the starting consumption is in a non-linear relationship with the outage time, e.g. for the boilers the following exponential relationship is used

$$B_{out} = B_i(1 - e^{-\alpha T}) \tag{7.12}$$

where B_i is the idle consumption; α is the coefficient depending on the boiler power P_B, e.g. for power units from 60 to 200 MW

$$\alpha = 21.3 \left(\frac{P_B}{100}\right)^{-0.585}. \tag{7.13}$$

Fuel consumption for starting cold non-modular boilers is assumed to be 0.65-0.8 of the rated load. For turbine-generator sets up to 50 MW the starting consumption of heat is $Q_{st} = 0.4\ P_T$ Gcal, where P_T is the turbine power, MW.

Now consider the effect of the boiler starts on its reliability. The number of starts is planned beforehand when drafting the year schedule and forecasting fuel consumption. In actual practice,

a daily stoppage of one or two units (night off-peak periods) is planned for all TPPs equipped with 100- or 160-MW units. On large thermal power stations one or two units can be additionally stopped on weekends. The 200- and 300-MW units are stopped after the potentialities of the 100- and 160-MW units have been exhausted, usually on weekends. From 500 to 700 annual startings are performed at the plants equipped with the units of the former type.

Frequent starts of the units are believed to decrease their reliability while the probability of an accident is increased in the course of starting because of a great number of operations to be accomplished by the attending personnel. Unfortunately such purely qualitative estimates, though seemingly obvious, are not supported by any actual analysis. To obtain experimental data, several units were detailed in the South-West Area Automatic Control Board for frequent outage operation. Each time when a necessity arose to stop a unit, it was one of them that was stopped. It is too early to draw any quantitative conclusions; however, the attending personnel could perform an additional inspection and minor preventive repairs of the stopped unit, thus improving reliability of its operation. If the starts are sufficiently frequent, the personnel gains necessary experience to perform them smoothly and without faults.

7.3. Equivalent Characteristics

The power system management problems widely utilize the equivalent characteristics of power plants which generalize some indices of the plant versus its operating conditions. Two types of equivalent characteristics are distinguished. The characteristics of the first type represent the relationship between index X and parameters Y, i.e. $X(Y)$, irrespective of time. These characteristics will be termed instantaneous since we assume that parameters Y are time independent. The characteristics of the second type, $X(Y, Z)$, which will be referred to as integral, reflect time variations of operating conditions and include parameters $Z(t)$.

Of the diversity of the energy characteristics of power plants and systems, we shall consider only those used in the principal optimization problems covered in this book.

Instantaneous energy characteristics of electric power plants define the relationship between the power input and useful power or between the indices in direct proportion to them. The indices depend on the unit availability and its loads. Other conditions being equal, highly efficient units obviously save more energy resources than the units of low efficiency. Distribution of load between units also affects the energy resource consumption and the best results are obtained only when the said distribution is optimal. The power plant char-

acteristic that would represent the unit availability, resistive and reactive loads, etc. can be obtained through the use of special optimization technique.

In case of a condensation power station with lateral thermal links, this problem is particularly challenging since one and the same output can be obtained at different variants of the heat balance. If a power plant includes two interconnected segments—a high-pressure and a medium-pressure segment—the medium-pressure turbines can be energized both from its boilers or from the boilers of both segments simultaneously. This problem requires the most elaborate solution methods. Besides, it necessitates construction of energy characteristics for a part of or all the boiler or turbine equipment of the plant.

The most complex are the characteristics of TPPs with lateral thermal links since, in addition to the mentioned above, they are drastically changed depending on the industrial or utility heat extraction. Without a computer and modern mathematical methods this problem cannot be solved in the full scope.

The instantaneous characteristics of the plant are constructed on the basis of the energy characteristics of the units. The algorithms of the plant characteristics are greatly dependent on the type of the unit characteristics. If the units can be represented by similar energy characteristics, the algorithm is fairly simple. On the contrary, units with different characteristics result in complex algorithms. The characteristic type dictates the choice of the optimization method. The algorithms of differentiable and monotonically increasing characteristics are simpler. The basic algorithms for constructing characteristics are given in Secs. 7.4 through 7.6.

Calculated integral characteristics of plants. The operating conditions of a power system are usually calculated with averaging the source information over discrete time intervals. In short-term planning, the data are averaged over intervals of several minutes to 1-3 h. Such an averaging causes some errors of the source information which are nevertheless reasonable so that the calculation results remain fairly accurate. The short-term calculations are performed with the use of instantaneous energy characteristics. The continuous operation calculations are quite another matter. For instance, the power system operation is known to be planned for a month, quarter and year in advance. The calculation interval in this case is one month, and the system loads, hydro plant inflows, economic and other indices are averaged over this interval. The averaging errors may distort the final results. One of the ways of improving the calculation accuracy is to employ the integral characteristics.

The integral characteristics are constructed for typical periods during which all the basic properties of the source information are

preserved and the effect of the input data upon the calculation results is not disturbed.

We shall explain the construction of the integral characteristic by way of example of planning long-term optimal operation of a hydro plant reservoir. For a hydro plant with an annual regulation, the operation of its reservoir should be planned a year in advance. The duration of the calculation period should be so selected that the inflow averaging errors are within the permissible limits. The low-water interval is usually one month, the flood interval is ten or five days. Naturally all other source data, including system loads, are subject to averaging. Averaging of the system loads, however, may cause impermissible errors in estimation of powers and required resources of HPs and TPPs of the system. For instance, the TPP fuel consumption depends considerably on daily and weekly load variations during a given month. The average characteristic $\overline{X}\,[\overline{Y},\ \overline{Z}\,(t)]$ for an interval is obtained by calculating the system operating conditions for typical periods, and the averaged operation parameter

$$\overline{X} = \frac{1}{n} \sum_{t=1}^{n} X_t(\tau_t) \tag{7.14}$$

where X_t are the instantaneous values of the parameter for points $t = 1, 2, \ldots, n$ during calculation period τ_t.

Accordingly

$$\overline{Y} = \frac{1}{n} \sum_{t=1}^{n} Y_t(\tau_t) \tag{7.15}$$

$$\overline{Z} = \frac{1}{n} \sum_{t=1}^{n} Z_t(\tau_t) \tag{7.16}$$

The construction of the interval average characteristics is discussed in Sec. 7.8.

Statistic characteristics of plants. The basic operation parameters and technical-and-economic indices are entered in the report documents of the power system. These documents are widely used for planning and analyzing the power system operation. For instance, when planning specific fuel consumption and water discharge, auxiliary power consumption of the plants, power production cost and other indices, the statistics of the past operation periods is of great importance. Processing the report data by the mathematical statistics and probability theory methods provides for obtaining the probabilistic characteristics and mathematical expectations of the above-mentioned indices, i.e. $\mathscr{E}(X)$, $\mathscr{E}(Y)$, $\mathscr{E}(Z)$. The methods

of regression-variance analysis make it possible to find the interrelation functions of the said values, i.e. the instantaneous and integral characteristics. Such characteristics are called statistic. The power plant operation may be described by a wide variety of statistic energy characteristics. For instance, in case of a hydro plant, the planner always constructs a relationship between the daily average water discharge and the daily average power at a fixed daily average head. The consumption characteristics may be obtained also for condensation power plants both with daily and monthly averaging of the parameters. The procedure for finding the statistic characteristics is outlined in Sec. 7.8.

The characteristics may be plotted both for the relative and differential indices. Relative indices, such as process efficiency or specific consumption of primary resource per unit useful power, are frequently used in calculations. These indices can be derived from any characteristic in absolute indices. If the instantaneous characteristics are used, it is possible to obtain instantaneous operating and differential characteristics. The interval average characteristics allow one to find the interval average operating and differential characteristics. And, finally, the statistic characteristics provide for calculating the mathematical expectations of the said values. The characteristic in absolute indices is primary in any case.

The interval average and statistic relative characteristics can also be obtained directly at the points for which the approximating function is selected with the aid of the regression-variance analysis technique. In such a case, primary will be the characteristics in relative indices. On some occasions, this improves the calculation precision since the relative indices are more responsive to the variations of the operating conditions.

7.4. Construction of Equivalent Characteristics by Dynamic Programming

In the general case, the characteristics of units of an electric station may have an arbitrary shape. For instance, the thermal unit consumption characteristics may have jumps, breaks, upward convexity, etc. (Fig. 7.1). The characteristics of hydro units may have plateaus, depressions, etc. (Fig. 7.2). Such characteristics cannot be differentiated, they do not rise monotonically which precludes or impedes the employment of gradient or variance methods widely used in various operation problems.

Plotting a power plant characteristic involves the analysis of the unit state. Each unit can be either in the ON or in the OFF state. If a plant includes n units, the number of states will be 2^n. Actual

plants, especially hydro plants, have $n = 10\text{-}25$ units, hence various combinations may give several thousand states. The problem can be solved by a mere exhaustion which is, however, awkward and difficult to accomplish even with the use of a computer. Therefore, the states should be analyzed by a method which would suppress the problem.

The technique meeting these requirements is called dynamic programming. It is suppressing, applicable to the unit characteristics of any type, and computer-oriented so as to ensure maximum economy of the machine memory and time.

There are algorithms for plotting instantaneous energy characteristics of HPs and unit TPPs by dynamic programming. They are methodologically similar for any station. Consider the case of a hydro plant.

Statement of the problem. Plot the equivalent optimal consumption (discharge) characteristic for HP, Q_{HP} (P_{HP}, H_{HP}) so that the optimal availability of the units and optimal power conditions of them are provided for any operating conditions with respect to power P_{HP} and head H_{HP}. The minimum water discharge will be the optimality criterion. The units have different energy characteristics Q_i (P_i, H_i) and power constraints.

In the general case, the problem is whole-numbered since only an integral number of units can be engaged, non-linear since the functions Q_i (P_i, H_i) are non-linear, and multi-extremum since there are several variants of unit engagement that would ensure the power balance of the station. The station characteristics are plotted on the basis of optimality of dynamic programming. This implies that the planner should find the optimal variant of the units availability and load distribution between them.

The mathematical model of the problem at H=const includes:

1. Objective equation

$$Q_j = \sum_i Q_i(P_i) \Rightarrow \min \tag{7.17}$$

where j is the number of the plant power conditions $P_j = P_1, P_2, \ldots$; i is the number of the unit.

2. Coupling equations—discharge characteristics of the units Q_i (P_i).

3. Constraint equations

plant power balance

$$P_j = \sum_i P_i \tag{7.18}$$

permissible ranges of plant power variation

$$P_{j,\min} \leqslant P_j \leqslant P_{j,\max} \tag{7.19}$$

permissible ranges of unit power variation

$$P_{i,\min} \leqslant P_i \leqslant P_{i,\max} \tag{7.20}$$

4. The optimization equation is set up using the optimality principle of dynamic programming.

The dynamic programming regards a variational problem as a multi-step continuous process. All the solutions of the subsequent steps should represent an optimal behaviour relative to the preceding steps (the recurrence procedure is used).

In the general case, at the ith step of the optimization of the availability and operation of the units, the principal functional equation of dynamic programming takes the form of a recurrence relation

$$Q_i^e (P_i^e) = \min \{Q_i (P_i) + Q_{i-1}^e (P_{i-1}^e)\} \tag{7.21}$$

where Q_i^e is the discharge by the equivalent characteristic at the ith optimization step for the HP powers P_i^e; Q_{i-1}^e is the discharge by the equivalent characteristic at $(i-1)$th optimization step for the plant equivalent power P_{i-1}^e; Q_i, P_i are respectively the discharge and power of the connected unit at the ith step of optimization.

Using the power balance equation, the functional equation is reduced to that in one variable P_i. Since the plant load P_j is known, $P_{i-1}^e = P_j - P_i$ and (7.21) takes the form

$$Q_i^e (P_i^e) = \min \{Q_i (P_i) + Q_{i-1}^e (P_j - P_i)\} \tag{7.22}$$

Thus the problem of optimizing a function of many variables is reduced to a multi-step optimization of a function of one variable P_i.

The calculation procedure includes plotting the equivalent characteristics of a given sequence of units $i = 1, 2, 3, \ldots, n$. The units can be considered in any sequence.

The characteristic of the first optimization step is a characteristic of the ith unit, e.g. $i = 1$. Later it will be optimized. The second step is the construction of the equivalent characteristic for two units operating in parallel. To this end, a combination of the known (given) characteristic of the first step and of the next unit from a given sequence, i.e. $i = 2$, is considered.

The optimization equation gives the equivalent discharge and equivalent power of these two units

$$Q_{i=1}^e \quad (P_i^e) = \min \{Q_2 (P_2) + Q_1 (P_j - P_2)\} \tag{7.23}$$

where the augend in the braces is the characteristic of the unit being connected $i = 2$, and the addend is the characteristic of the first step of optimization.

Varying power P_2 at $P_j = \text{const}$, we can obtain such a distribution whereat function (7.23) is minimized. If such calculations are

carried out for different P_j within the range of possibilities of two units, we obtain the equivalent characteristic of the second optimization step $Q^e_{i=1,\,2}\,(P^e_i)$ which is the characteristic of units $i = 1, 2$. The characteristic may include points of separate and joint operation of the units. The only criterion is the minimum water discharge. Next the equivalent characteristic is plotted for three units $i = 1, 2, 3$ with the aid of the equation

$$Q^e_{i=1,\,2,\,3}\,(P^e_i) = \min\,\{Q_3\,(P_3) + Q^e_{i=1,\,2}\,(P_j - P_3)\} \quad (7.24)$$

Here the third unit $i = 3$ is connected and considered with respect to joint operation with a hypothetical unit having the characteristic $Q^e_{i=1,\,2}\,(P^e_i)$. Varying power P_3, we can find the optimal solution alternately for all P_j within the operation range of the three units and plot the equivalent characteristic $Q^e_{i=1,\,2,\,3}\,(P^e_i)$. The calculations may give operating conditions with engagement of one unit, combinations of two units or joint employment of all three units. Next the calculations are repeated with increasing the unit number by 1 at each step. Thus a great number of calculation steps is needed to plot the equivalent characteristic. In the general case the number of calculations is

$$m = \sum_i (ki + 1)\,ki \quad (7.25)$$

where k is the number of steps of power ΔP used in calculations, i is the step number.

It is clear from (7.25) that plotting of a characteristic, e.g. for the Krasnoyarsk Hydro having 12 units and a total power of 6000 MW, with a step of 10 MW, requires about 2 million operations practicable only with the use of computers. These calculations are simple arithmetical operations, so their number will present no difficulty for a machine. The problem of plotting and storing the equivalent characteristics is far more challenging. The optimal operating conditions are found by the return procedure which drastically diminishes the memory capacity required to store the equivalent characteristics. To find the optimal solution it suffices to store for each plant power P_j only the number and load of the unit connected to the equivalent unit at a given power, rather than numbers and loads of all the operating units.

For instance, a characteristic was constructed for a plant having four units at a sequence of $i = a, b, c, d$. At a plant load P_1, the computer holds the number and power of the unit being connected, e.g. unit d and power P_d. Then the equivalent unit has the power $P^e_1 = P_1 - P_d$. A new point corresponding to the power P^e_1 is found on the characteristic. Let unit b of power P_b be connected at this power, then the equivalent unit at the plant power P^e_1 has the power $P^e_2 = P^e_1 - P_b$. At last, for the characteristic point P^e_2, we

obtain, e.g. unit a with power P_a. If $P_2^e = P_a$, the calculations are completed.

The return run procedure decreases manifold the computer memory required for storing the energy characteristics. Still it remains great in many instances. For the Krasnoyarsk Hydro the characteristic should have 600 points. Each point includes at least the value of water discharge of the station, power and number of the unit being connected, i.e. three numbers (all other parameters can be found by computation) so that a total of 1800-2000 numbers are to be memorized. Such problems can be handled only by the computers of appropriate class. If the computer capabilities are not sufficient, the number of the characteristic points has to be decreased, which decreases the accuracy of construction.

This algorithm is realized on a computer and is essentially the only one today which solves two problems simultaneously: optimization of the availability and optimization of the operation of the units. The same algorithm is applicable for plotting equivalent characteristics of unit TPPs, plant segments, group of plants when the power network losses are neglected or approximated.

7.5. Plotting of Equivalent Characteristics for Assigned Availability of Units

If the availability of the operating units is known, optimization problem is confined to finding the optimal distribution of load between the units.

For units with characteristics in an arbitrary form the dynamic programming algorithm is used. Constraint (7.19) should be assigned to prevent inadvertent switching-off of any one of the units. With such a constraint the power of each unit will never drop below the given minimum value $P_{i,\ \min}$. For instance, in case of the availability and sequence $i = 1, 2, 3$, the calculations are carried out as follows. First plot the equivalent characteristic for two units according to (7.21). Varying the second unit power P_2 with a given step, perform an exhaustive search of all the distribution variants to find the one minimizing water discharge. The next step is also an exhaustive search of variants of load distribution between unit *3* and the equivalent characteristic of the second step. The exhaustive search is naturally far from being the best optimization method, though a computer copes with such calculations easily because of their logic simplicity.

The method of plotting equivalent characteristics with the aid of the incremental rate technique looks simpler but is applicable only for units with differentiable and monotonically increasing characteristics.

When the available units are known, the load is distributed between them on the basis of equality of incremental rates or the units with a lower incremental rate (if no such equality exists) are loaded first. Using this rule, we can obtain the equivalent characteristic of incremental rates and equivalent discharge consumption characteristic of a station or group of stations.

Figure 7.11 shows an example of plotting the equivalent consumption characteristic for two thermal units *1* and *2*. The plant minimum power P_{min} is determined by the minimum power of both units.

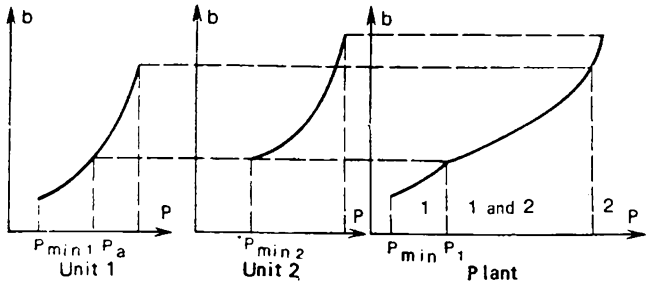


Fig. 7.11. Equivalent characteristic of two units

When the plant power is increased to P_1, the first unit is loaded to P_a because it features a lower incremental rate. In the power region from P_1 to P_2, both the units are loaded according to the incremental rate equality principle, when the power exceeds P_2, unit *2* is loaded. Thus, the equivalent characteristic of incremental rates is plotted. It provides all the necessary data for constructing the equivalent consumption characteristic, i.e. allows one to determine the unit power corresponding to the minimum consumption of fuel at any load of the station. This method is simple, readily computable and therefore finds wide application especially for plotting equivalent characteristics of incremental rates.

The characteristics of incremental rates are used for optimization calculations and, as a rule, should meet the requirements of differentiability and monotonic increase. These requirements are not satisfied on most occasions so that special procedures have to be used to transform the characteristics to a suitable form.

If the characteristics feature the discontinuity of the first type (Fig. 7.12*a*), any incremental rates from b_1 to b_2 correspond to power P_1, i.e. relation b (P) is ambiguous and the solution will be indeterminate. To get rid of the indeterminacy, the characteristic is represented by two isolated parts OA and BC. When the unit power is less than P_1, the unit is defined by part OA, when it is equal to or exceeds the said power, by part BC.

The characteristics with the discontinuities of the second type (Fig. 7.12*b*) can be transformed by a simple technique based on the assumption that redistribution of load of the plant being considered does not change the incremental rate of the system as a whole. This holds good only if the plant contribution to the system power balance is not great.

Now assume that a station with a characteristic shown in Fig. 7.12*b* operates in a large system having a constant incremental rate $b_s = \text{const}$ (Fig. 7.13) irrespective of the station load. When the load

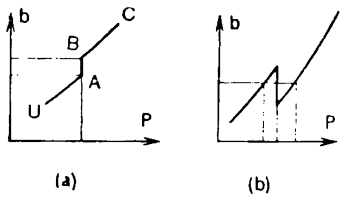


Fig. 7.12. Two types of discontinuity in incremental rate characteristics

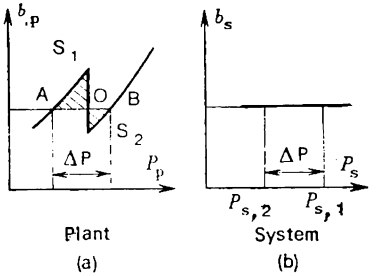


Fig. 7.13. To methods of eliminating discontinuity in incremental rate characteristics

distribution is optimal, the station incremental rate will also be b_s but it will correspond to the powers P_1 and P_2. The question is which of these two powers is optimal. Two power balance variants are possible for the system:

$$P = P_{s\ 1} + P_1$$
$$P = P_{s,\ 2} + P_2$$

where P is the system load; $P_{s,1}$, $P_{s,2}$ are the powers of all the stations except the one being considered.

When changing over from power P_1 to power P_2, the plant fuel consumption will increase, whereas the consumption of fuel for the entire system will drop, i.e. the total change in the fuel consumption

$$\Delta B = \int_{P_1}^{P_2} b_s\, dP - b_s \Delta P = b_s \Delta P + S_1 - S_2 - b_s \Delta P = S_1 - S_2 \quad (7.26)$$

where S_1 and S_2 are the shaded areas in Fig. 7.13.

We will refer to S_1 as the excessive consumption area, and S_2 as the fuel economy area. If $\Delta B > 0$, it is unfeasible to increase power from P_1 to P_2, because this would result in excessive fuel

consumption. At $\Delta B < 0$, the fuel would be saved, and at $\Delta B = 0$, all the variants would give equal economy. Use this postulate to bring the characteristic b (P) to the required form.

At the system incremental rate b_1 (Fig. 7.14), $S_1 > S_2$ $(S_2 = 0)$, i.e. power P_1 is more feasible. At b_2, $S_1 > S_2$, i.e. power P_2 yields more economy; at b_3, $S_1 = S_2$, P_3 and P_3' are of equal economy; at b_4, $S_1 < S_2$, power P_4' is economic, at b_5, power P_5'.

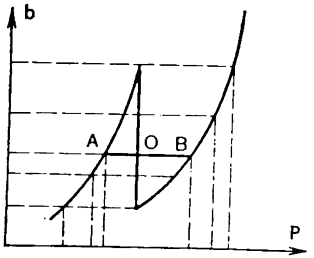


Fig. 7.14. Elimination of discontinuity in incremental rate characteristic

The incremental rates $b_1<b_2<b_3<b_4<b_5$ are plotted as ordinates; the powers $P_1<P_2<P_3<P_3'<P_4'<P_5'$ as abcissas

Thus to eliminate discontinuity of the curve in Fig. 7.14 it is sufficient to trace the line b = const so that $S_1 = S_2$. Now at lower incremental rates, refer to the left-hand branch, with higher rates to the right-hand branch.

It is easy to demonstrate that operation in zone AB (Fig. 7.14) always involves excessive consumption of fuel. Actually $S_2 > S_1$ in this area irrespective of the power, and the excessive consumption is maximum at the curve discontinuity point since $S_2 = 0$. Therefore, zone AB is the zone of undesirable operation. In actual practice, however, this zone is not excluded since excessive consumption

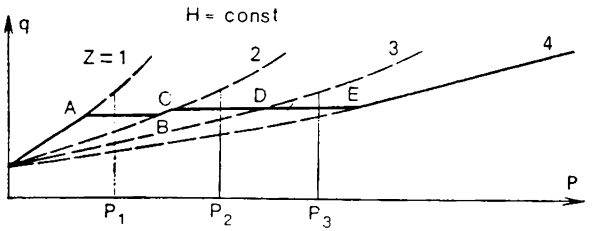


Fig. 7.15. HP differential characteristic (z stands for number of available units)

of fuel usually does not exceed 5-10% of the possible economy, while prohibiting the use of the plant in it causes tremendous operation inconveniences and decreases reliability of the entire system.

The reliability characteristics of TPP are shown in Fig. 7.11, those of HP in Fig. 7.15. The latter shows a characteristic of HP with four units. The unit cut-in points display discontinuities. To eliminate the discontinuities, lines AB, CD, DE are traced so that the plateaus over and under them are equal. Zones AB, CD, DE are the zones of undesirable operation, and eliminating the respective powers of HP is theoretically grounded. However, such a solution

would drastically restrict the regulating ability and slewability of HP, hence decrease the system reliability; to avoid this, all the conditions are regarded tolerable for HPs.

Plotting the equivalent consumption characteristics against the equivalent differential curves suffers from some drawbacks. The incremental rates (differential indices) are extremely sensitive to all kinds of errors in the source information, plotting calculations, and the like. Therefore, the incremental rate characteristics may be inaccurate to 5-10% or even more. The operating conditions found from such characteristics may differ from optimal, hence the equivalent consumption characteristic may involve gross errors. The dynamic programming technique eliminates these drawbacks since it uses the characteristics in terms of absolute indices.

7.6. Construction of Equivalent Characteristics for TPPs with Lateral Coupling

In case of a plant with a complex thermal circuit (Fig. 7.16), the optimal solution is determined not only by the availability of turbines and boilers but also by their thermal circuits. Because of its

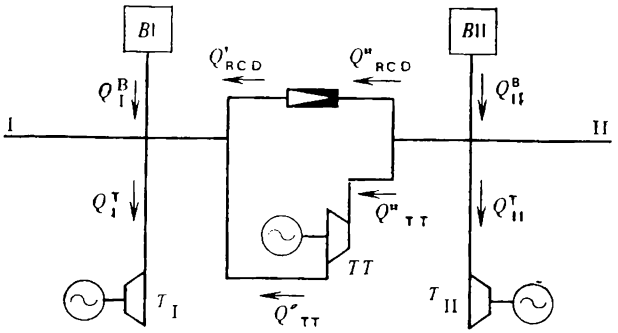


Fig. 7.16. Diagram of thermal power plant

great dimensions, the problem is usually solved by a simple or directed exhaustion and is confined to the construction of a characteristic library with various actual boilers and turbines.

Figure 7.16 represents a typical diagram of TPP equipped with turbines T of different types and boilers B of two different pressures. The plant segments are interconnected by a topping turbine TT and a reducing-cooling device RCD. Other schemes are particular cases of the diagram shown in Fig. 7.16.

The simplest of the particular cases is a plant with turbines and boilers of the same pressure operating with a common steam line. The characteristic for such a plant is constructed as follows. The

optimal availability and operating conditions of turbines are selected for the given loads and the equivalent characteristic of the turbines is plotted. Next the optimal availability and conditions of the boilers to ensure normal operation of the turbines are found and the equivalent characteristic is constructed for the boilers. Proceeding from the equivalent characteristics of the turbines and boilers, the equivalent characteristic of the plant is determined. As a rule, the boilers and turbines available within the limits of one characteristic are not changed. The availability and conditions of the units may be optimized using the methods of incremental rates, dynamic programming, and the like.

Another particular case is a plant having turbines and boilers of two pressures with their steam lines being interconnected via an *RCD*. The number of possible solutions for such a plant rises because the lower-pressure turbine can be fed from the boilers of both segments (from the higher-pressure boilers through an *RCD*). This complicates calculations for selecting the boilers.

In the general case (Fig. 7.16), the segments of different pressure are interconnected via *RCD* and *TT* which still more increases the dimension of the problem. Actually, turbines T_I can be fed with thermal energy by one of the following schemes: from boilers B_I; from boilers B_{II} via *RCD*; from boilers B_{II} via *TT*; from boilers B_{II} via *RCD* and *TT* at various distribution of the requisite thermal energy; from B_I and B_{II} via *RCD*; from B_I and B_{II} via *TT*; from B_I and B_{II} via *RCD* and *TT* with various distribution of energy fed from B_{II} to the lower-pressure segment. At present the thermal scheme is accounted for by using the directed exhaustion method. The directed exhaustion principles are usually determined on the basis of engineering experience for the particular conditions so that the algorithms are very awkward and fail to offer adequate accuracy.

Consider an example of such an algorithm. If the load distribution is optimized, all the plants of the system operate with the incremental rate b_s. Assume that during loading of the plant under discussion $b_s = \text{const}$. Then, the optimal operation of the thermal power plant occurs when the function

$$F = B_p - b_s P \Rightarrow \min \qquad (7.27)$$

where B_p is the plant fuel consumption obtained for different variants of the available turbines and boilers; P is the plant load.

Mathematical model. 1. Function (7.27) is the objective equation and can be written as:

$$F = B_I (Q_I^T + Q'_{TT} + Q'_{RCD}) + B_{II} (Q_{II}^T - Q''_{TT} - Q''_{RCD}) - b_s (P_I + P_{II} + P_{TT}) \Rightarrow \min \qquad (7.28)$$

2. The coupling equations include consumption characteristics of turbines $B_{T,\,i}$ $(Q_{T,\,i})$; consumption characteristics of boilers $B_{B,j}$ $(Q_{B,\,j})$; characteristic of RCD Q'_{RCD} (Q''_{RCD}).

3. Constraint equations:

(a) the operating variables are restricted by the constraints in the form of inequalities

$$Q^T_{i,\min} \leqslant Q^T_i \leqslant Q^T_{i\ \max};\ Q^i_{TT,\ \min} \leqslant Q'_{TT} \leqslant Q'_{TT,\ \max};$$

$$Q'_{RCD,\ \min} \leqslant Q'_{RCD} \leqslant Q'_{RCD,\ \max};\ Q^B_{j,\ \min} \leqslant Q^B_j \leqslant Q^B_{j,\ \max}$$

where i = number of the turbine

j = number of the boiler

(b) the thermal energy balance equations (constraints in the form of equations)

$$Q^B_{\mathrm{I}} = Q^T_{\mathrm{I}} + Q'_{RCD} + Q'_{TT}$$

$$Q^B_{\mathrm{II}} = Q^T_{\mathrm{II}} - Q''_{RCD} - Q''_{TT}$$

where Q^T_{I}, Q^T_{II}, Q^B_{I}, Q^B_{II} = heat consumption of the turbines and boilers of the first and second segments

Q'_{TT}, Q''_{TT} = heat consumption of the topping turbine at inlet and outlet

Q'_{RCD}, Q''_{RCD} = heat consumption through RCD at inlet and outlet

(c) the power balance equation (equation constraint)

$$P = P_{\mathrm{I}} + P_{\mathrm{II}} + P_{TT}$$

where P_{I}, P_{II}, P_{TT} = electric power of the first and second segments of the plant and of turbine TT

4. The optimization equation is on the one hand a preselected logic pattern for finding the combinations of the units and values of heating and industrial extraction of heat from the turbines and on the other, the equations of the incremental rates for the units, used for optimal distribution of loads between the given turbines or boilers.

The optimization equations take the form of minimum fuel consumption of the thermal power plant at state variables R, i.e.

$$B\ (R)\ \} = \min \tag{7.29}$$

with the provision that

the incremental rates are equal for the turbines of both segments of the plant and the topping turbine

$$d^T_{\mathrm{I}} = d^T_{\mathrm{II}} = d_{TT} = \text{idem} \tag{7.30}$$

the incremental rates are equal for the boilers of both segments of the plant

$$d_{\mathrm{I}}^{B} = d_{\mathrm{II}}^{B} \tag{7.31}$$

the incremental rates of the first and second segments and the topping turbine are equal

$$b_{\mathrm{I}} = b_{\mathrm{II}} = b_{TT} = \text{idem} \tag{7.32}$$

The optimization is performed as follows. Assign the variants of the available turbines and boilers forming vector **R**. With the available turbines being known, find the equivalent characteristics and optimal distribution of load between the turbines of the first and second segments from their incremental rate equation (7.30). Proceed similarly to construct the equivalent characteristics and find the optimal distribution of load between the boilers (7.31). Next plot the equivalent characteristic of the plant incremental rates against (7.32), and finally, the equivalent consumption characteristic.

The program prepared on the basis of this algorithm was used to set the TPP characteristic library of several power systems. Table 7.3

Table 7.3

TPP Characteristic Libraries

System	Number of plants with libraries		Number of plants with two types of fuel	Number of calculated characteristics	Number of characteristics in a TPP library
	CPP	TPP			
Mosenergo	3	7	5	1600	80-300
Central IPS	7	23	10	1763	40-200
South IPS	12	—	2	500	20-73
Donbassenergo	6	—	1	260	20-73

represents the data of such libraries which include only usable characteristics rather than all possible ones.

Evidently, a characteristic library cannot be obtained by manual calculations. The characteristics have to be updated as the units age and are modified, heat extraction changes, etc. which requires systematic calculations.

7.7. Average Interval Characteristics

The optimization of the long-term operation of power systems involves considerable difficulties. A long period of calculations (from a month to several years) makes the planner enlarge the time intervals of calculation and to diminish the error of calculations caused by such an enlargement, the average interval characteristics

of thermal and hydro power plants are used. These characteristics reflect particulars of the short-term (hourly, daily) operation of the plant within the calculation intervals which allows one to account for the impact of the short-term operating conditions on the long-term ones.

The average interval characteristics may be used in various systems problems. For instance when elaborating a draft plan of the power system a year or a year and a half in advance, the average interval characteristics can be of help in calculating the basic technical-and-economic indices of the system, such as specific and absolute consumptions of fuel for the electric power and heat generation, production cost, profit, etc. The average interval characteristics are also usable for scheduling major repairs, allocation of the system reserve, etc. All the long-term problems of the system management are usually solved with enlarged intervals of calculation so that the information fed from the plants should represent the daily operating conditions, which dictates the use of the average interval characteristics, especially if the variation of the system parameters or conditions invalidates statistical characteristics.

To construct the average interval characteristics, it is assumed that the typical daily load curves of the system are given and the calculations are based on the short-term (daily) optimization of the system operation.

Let us consider the construction of the average daily characteristics for a mixed power system with a fixed-head hydro plant. The daily operation is calculated by the program of the optimal distribution of load between the stations with the use of the Lagrange multiplier technique (see Ch. 6).

Let the daily load curve be known and optimally distributed between the plants of the system. Assume that the system comprises one equivalent thermal power plant and one hydro. Then the said optimal operation corresponds to $\overline{B}$, $\overline{Q}$, λ (the overhead dash indicates the average daily values of the parameter). Performing such calculations for different water discharge rates and λ, we obtain relations $\overline{B}\ (\overline{P}_{TPP})$, $\overline{Q}\ (\overline{P}_{HP})$, $\lambda\ (\overline{Q})$, i.e. the average daily characteristics of, TPP and HP and the characteristic of the water resource utilization in the system.

Average daily characteristics of plants in all-thermal power system. To plot characteristics $\overline{B}_i$. $(\overline{P}_{TPP,i})$ for $i = 1, 2, 3, \ldots, n$ TPPs, a constraint to utilization of heat resources can be introduced. First solve the problem of optimal distribution of load between all TPPs with the provision that b_i = idem and without fuel constraint. Then, say for the jth plant ($j \in i$), set a constraint

$$B_j = \sum_t B_{j,t} = R$$

where R is the resource constraint.

Varying R, we can determine a higher or lower load for a given station as compared with the initial variant without a constraint. These calculations will give the average daily characteristics $\overline{B}_i$ ($\overline{P}_{TPP.\,i}$) providing for the construction of the average daily characteristics of TPP incremental rates.

The role of implementing the operating conditions determined with the use of the average interval characteristics is very important. In many instances, deviation of the actual information from the planned data introduces errors that cannot justify the use of the average daily characteristics. Thus, a forecast of a system load for a year can prove inaccurate up to 20% so that the effect of using the average daily characteristics becomes very doubtful.

7.8. Statistic Characteristics

The statistic information accumulated in the course of operation allows one to discover the relations between the energy parameters. For instance, the thermal power plant information includes hourly, daily, monthly powers, fuel consumption, heat extraction, specific fuel consumption, etc. In case of hydro plants, there are data on the water discharge rates, powers of units and stations, water heads, etc. Various characteristics can be constructed by analyzing the statistics.

The methodology of receiving and processing information for the power system control problems is based on the probabilistic and indeterminate nature of information and utilizes classic techniques. Besides, the statistic characteristics are used on the assumption that no substantial changes will occur in the power plant operation during the forthcoming period. Should the operating conditions of the system, the role played by separate stations, technical or economic characteristics and indices be changed, the statistic data accumulated during the preceding periods can become fully or partially invalidated.

To set the statistic relations, three main statistic problems are usually solved:

(1) determination of the mathematical expectation, variance and rms deviations of the parameter;

(2) search of the approximating function of the parameter relation;

(3) determination of characteristic changes caused by separate factors.

The statistic problems are labour-consuming, therefore constructing the energy characteristics of units and plants is feasible only with the use of computers. MCS offers favourable conditions for handling these problems. The data bank being a component of MCS rules out the need for special preparation of statistic data. Moreover, the characteristics are periodically updated as new information is stored.

The statistic energy characteristics are plotted for typical conditions. They can change with seasons and months depending on the available power of the plant, fuel type, etc. The typical conditions are usually determined beforehand by data analysis.

Let us consider several problems of constructing statistic energy characteristics of electric power plants.

Statistic discharge characteristics of hydro plant. The statistic characteristics of a hydro plant, based on the average daily discharge $\overline{Q}$, power $\overline{P}$ and head $\overline{H}$ have been long and widely used to solve various problems. For instance, such characteristics are usually employed to determine power and amounts of electricity generated, to compile the reservoir emptying and filling schedules, etc. Based on the average daily information, they are representative of the available unit operation, fluctuations of the head and tail water levels, changes of the station reactive load, clogging of trash racks and many others. The statistic characteristics differ from instantaneous ones; for instance, other conditions being equal, the discharge rates for the Novosibirsk Hydro expressed by these two types differ by 5 to 10%.

The average daily values of $\overline{Q}$, $\overline{P}$, $\overline{H}$ are used to select the approximating function. If the function $\overline{Q}(\overline{P})$ is selected at $\overline{H} = \text{const}$, a sufficiently accurate approximation is ensured by the polynomials of the second or third degree

$$\overline{Q}(\overline{P}, \overline{H}) = \sum_i \sum_j a_{i,j} \overline{P}^i \overline{H}^j \qquad (7.32a)$$

where $a_{i,j}$ are the polynomial coefficients.

The principal drawback of such characteristics is that they represent both the optimal and non-optimal solutions. When the characteristics are used for estimation, this drawback is not too grave; for the optimization purposes, however, their reliability is often doubtful. MCSs easily rectify this shortcoming if the operation effectiveness is constantly monitored so that the deliberately erroneous (unfeasible) conditions are neglected. Of course the "bad" conditions can also be included in the statistic characteristics if dictated by some particulars of system operation. These aspects call for special attention.

The accuracy of statistic characteristics of a hydro plant improves if they are constructed for the typical hydrological conditions (low water, flood) and periods of system operation (winter, spring, summer, autumn).

Statistic consumption characteristics for thermal power plant. The TPP statistic characteristics reflect not only a diversity of the available unit operating conditions, variation of loads, technical-and-economic indices, but also unsteadiness of the thermal loads of the station. The TPP consumption characteristics are of two types:

$\overline{B}_E$ $(\overline{P})$ and $\overline{B}_H$ $(\overline{Q}_H)$, where $\overline{B}_E$ is the average interval consumption of fuel for electricity; $\overline{B}_H$ is the average interval consumption of fuel for heat; $\overline{Q}_H$ is heat extraction.

Fuel distribution between the electricity and heat is carried out by a physical method which cannot fully represent the electricity generation at a thermal plant so that relations $\overline{B}_E$ $(\overline{P})$ and $\overline{B}_H$ $(\overline{Q}_H)$ are not always explicit. A more explicit is the relation $\overline{B}$ (Q), where $\overline{B} = \overline{B}_E + \overline{B}_H$, and Q is the total consumption of heat with recalculating power P to its thermal equivalent.

The statistic consumption characteristics are widely used for planning. Figure 7.17 shows the statistic characteristics for TPPs of

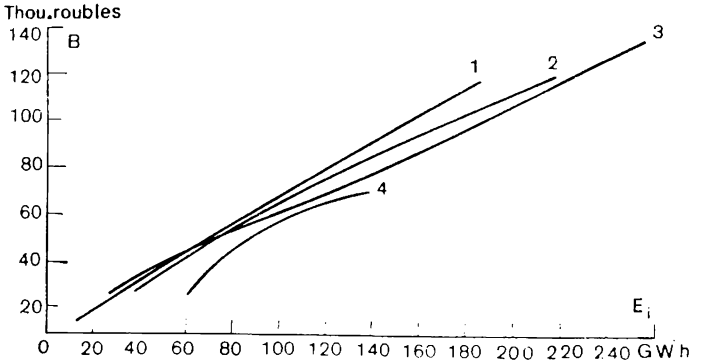


Fig. 7.17. Statistical characteristics of fuel consumption vs electricity generation for TPP of Novosibirskenergo system

1—regression equation $B = 5.0429 + 0.5974E$; *2*—$B = 8.5578 + 0.6904E - 0.00065E^2$; *3*—$B = 9.0824 + 0.3834E + 0.00025E^2$; *4*—$B = -28.3538 + 0.9421E - 0.00197E^2$

the Novosibirsk system, which were constructed on the basis of monthly intervals.

In many systems, TPPs operate in the base-load or half-peak part of the load curve and the unsteadiness of the statistic characteristics for them is mainly determined by the station factors. Analyzing their impact on the station indices, the planner can find ways to improve the effectiveness.

Statistic characteristics based on current data. This problem was originated in the depths of power plant APCS. Monitoring the parameters of the units and stations, processing and analyzing the current information allow one to refine the energy characteristics of separate units.

The statistic characteristics of the units can be the starting point for calculating the characteristic of the plant. Large body of experimental data is needed to solve the problem. According to the validity the information is divided into three groups:

1. Determinate data X_e^d obtained from sensors or computed during operation of the plant.

2. Probabilistic data X_e^p calculated from statistic (correlating) relations.

3. Uncertain data X_e^u which cannot be calculated from the data of current operation of the plant but can be sometimes forecasted.

The form of the relation between a definite parameter of operation Φ and the experimental information is set a priori, i.e. we know the function $\Phi\ (X_e^d,\ X_e^p,\ X_e^u)$. Knowing the single value of X_e^d, the value of Φ can be found by determining the mathematical expectation of the probabilistic factors $\mathcal{E}\ (X_e^p)$ and using the forecast X_e^u in the determinate or probabilistic form.

Let us consider examples of refining characteristics for TPPs and HPs. At the Zmievka, Moldavian and some other regional thermal power stations the energy characteristics of the power units are calculated and refined on the basis of the current data.

The variables $X_1,\ X_2,\ \ldots,\ X_n$ determining operation of the unit are found from the experience gained and the statistic analysis. If the actual fuel consumption of TPP corresponds to B_a, while calculation against the principal factors gives a different value of $B\ (X_1,\ X_2,\ \ldots,\ X_n)$, the relation

$$\sum_j (B_j - B_{a,j}) \Rightarrow \min \tag{7.33}$$

can be verified to the accuracy of characteristic approximation.

Assigning a certain significance level for influence upon B_j by the particular values, we can select the decisive factors which ensure the required precision of condition (7.33). Thus, for the unit of the Zmievka thermal power station, the variables comprise the active power of the generator, relative vacuum of the turbine, exhaust gas temperature, feedwater temperature, exhaust gas oxygen content and air flow rate.

Information $X_1,\ \ldots,\ X_n$ is entered into the computer memory at 15-s steps, however, to eliminate the dynamic processes the data are averaged on the 15-min interval basis. The variance analysis allows one to select the most valid data.

The consumption characteristic of the unit is set as a piecewise-linear function of the form

$$B = a_0 + a_1X_1 + a_2X_2 + \ldots + a_nX_n \tag{7.34}$$

where $a_0,\ a_1,\ \ldots,\ a_n$ are the constant multipliers found during approximation by the least-square method.

Thus, the fuel consumption corresponding to the measured power P of the unit is calculated from (7.34) thus providing for plotting the entire characteristic.

A similar problem is considered for a hydro station. The energy characteristics of the hydro units are modified depending on the following values: head losses in the trash racks Δh_r, generator efficiency variations caused by its cos φ, head changes stemming from unsteady tail water ΔH_{t-w}, decrease of the turbine efficiency because of cavitation wear $\Delta\eta_T$. The values Δh_r, $\Delta\eta_T$, ΔH_{t-w} are regarded random as being dictated by a plurality of technical, natural and economic factors. The statistic analysis has revealed that these values correlate as X_i (P_u), where X_i is a random value, and made it possible to find mathematical expectations $\mathscr{E}$ (X_i) for constant powers P_u. The value of $\Delta\eta_T$ is determinate. Using mathematical expectations $\mathscr{E}$ (X_i) and $\Delta\eta_T$, unit water discharge Q_u at power P_u is corrected. The dependence Q_u (P_u) is determined beforehand. Figure 7.18 shows the initial and corrected curves of the unit of the Novosibirsk Hydro.

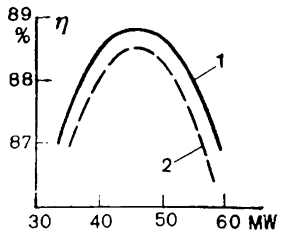


Fig. 7.18. Performance characteristics of unit at the Novosibirsk Hydro ($H = 17$ m)
1—initial; *2*—with statistical corrections

7.9. Approximation and Storage of Characteristics

Let us consider some methods of approximation of the energy characteristics of units, power plants and systems.

Processing of test results. The energy characteristics are obained experimentally by measuring the unit parameters. There are two types of experiments: passive and active.

In the *active experiment* the power unit is brought to certain operating conditions beforehand and is maintained under them for a sufficiently prolonged time to exclude the transient thermomechanical processes. Then all the parameters to be checked are measured as simultaneously as possible. Measurements of the active power and pulverized fuel consumption present a severe problem. After a run of measurements carried out with a view to deleting random mistakes and unreliable results, the unit is changed over to other operating conditions and the measurements are repeated. After the tests are completed, their results are processed. If some parameters measured during the tests differ from the rated values, special fuel consumption or active power corrections are introduced.

The active experiment is rather labour-consuming and expensive. It is usually restricted to the leading units of the power plant or system, while the characteristics of other units are assumed to be similar or the so-called typical characterisics are used, i.e. those

specified by the equipment manufacturer. Despite its complexity and cost, the active experiment does not guarantee the accuracy because its artificial conditions (e.g. artificially steady operation during the tests) may differ radically from the actual practice when frequent fluctuations of load are possible. The active experiment can be performed at any station, including those having no computers. Of course, the use of a computer in the centralized monitoring mode substantially facilitates the experiment.

The *passive experiment* resides in that the unit characteristic is calculated under actual operating conditions of the plant which need not meet any particular requirements. The passive experiment is feasible only at computerized stations.

Consider a passive experiment carried out on a unit burning gas or fuel oil. Fuel consumption is easy to determine in this case. Assume that each unit is equipped with the required number of sensors for measuring the operating variables (100-200 sensors per unit and even more).

Calculation of fuel consumption. Fuel consumption and electric power of the unit $\{B_i, P_i\}$ are measured directly or calculated proceeding from the sensor information. If the unit operates on pulverized fuel, its consumption cannot be measured directly and should be calculated by the reverse balance data. Three types of fuel loss components are to be measured. The most challenging problem is to find out the completeness of combustion, though, a special sensor has been recently devised.

The organization of storage of the tested points in the computer memory gains special importance. Storing all the computed values of the pairs of points $\{B_i, P_i\}$ makes no sense, therefore only some averaged values are memorized. To preclude excessive errors, averaging is performed within a limited parameter variation range (Fig. 7.19).

To this end the entire working range of power variation is divided into a number of intervals (squares). In each interval only one averaged value of the consumption characteristic point is stored. The measured point belonging to the interval is checked against the said averaged value each time the data are processed. If the calculated fuel consumption is reasonably inside the preset range $B_{i,\max}$, $B_{i,\min}$, the unit operation during the observation period was sufficiently stable, the transient processes were negligible and the point can be used in the experiment, i.e. can be added to the measurement results. A new consumption within a given power interval is found from the averaging formula

$$\overline{B}_{i,(k+1)} = \frac{a_1 \overline{B}_{i,k} k + B_{i,k+1} a_2}{k+1} \qquad (7.35)$$

where a_1 and a_2 are certain coefficients, usually $a_2 > a_1$; k is the measurement number; $\bar{B}_{i,k}$ are the averaged fuel consumption at a given step.

Prior to averaging, the fuel consumption is reduced by linear interpolation to the power in the middle of the interval, i.e.

$$B_k = B_{k,a} \frac{P_i}{P_a} \tag{7.36}$$

This technique allows for storing only one point representative of the entire square (Fig. 7.19*b*).

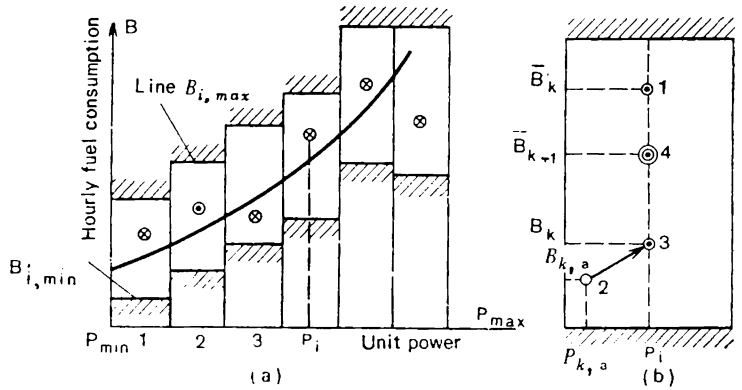


Fig. 7.19. Storage of averaged points in approximation of thermal power unit characteristic

(*a*) discrimination of zones (blocks); (*b*) sequence of point process within zone: *1*—averaged point stored at the kth measurement; *2*—$(k+1)$th instantaneous measurement; *3*—measurement result recalculated to the middle of interval; *4*—averaged point of the $(k+1)$th measurement placed in storage

Approximation of characteristics. After a sufficiently long experiment, a series of pairs of points $\{\bar{B}_i, \bar{P}_i\}$ is obtained and the points should be connected by a smooth curve. To this end assume a fuel consumption-vs-power relation, e.g. a second-degree polynomial

$$B_i = \tilde{a}_i + \tilde{b}_i P_i + \tilde{c} P_i^2 \tag{7.37}$$

Substitute the measured power P_m and calculate fuel consumption $B_c = \tilde{a}_i + \tilde{b}_i P_m + \tilde{c}_i P_m^2$. The calculated consumption differs from the measurement results. The difference $\Delta B = B_m - B_c$ defines the imbalance

$$\Delta B = \tilde{a}_i + \tilde{b}_i P_m + \tilde{c}_i P_m^2 - B_m$$

Raise the both sides of the equation to the second power

$$\Delta B^2 = (\tilde{a}_i + \tilde{b}_i P_m + \tilde{c}_i P_m^2 - B_m)^2$$

Sum up the measurement results of all k experiments

$$\sum_k (\Delta B_i)^2 = \sum_k (\tilde{a}_i + \tilde{b}_i P_{m,k} + c_i P_{m,k}^2 - B_{m,k})^2 \qquad (7.38)$$

The task now is to select coefficients a, b and c as to minimize the squared imbalance

$$\sum_k (\Delta B_i)^2 \Rightarrow \min \qquad (7.39)$$

Particular cases of approximation. When approximating the consumption characteristics by the data of special tests of the boiler, the number of points is usually limited since each test is rather long and expensive. The curve traced through the measurement points, e.g. with respect to the minimum square deviation, may be not unique. When plotting such a characteristic, the planner usually assumes an additional hypothesis of the curve form which should be in accord with the optimization method in use. For instance, it is often considered that with convex programming methods the curve should be convex, or that it can be approximated by a polynomial of a sufficiently low degree, or that it should take a certain probable known form, etc. Figure 7.20 illustrates how the use of different hypotheses leads to different forms of the energy characteristics of a boiler. The curves are plotted by the same test points.

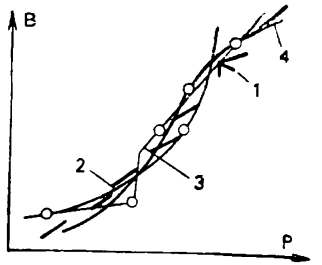


Fig. 7.20. Approximation of energy characteristics with different a priori information

1—linear function; *2*—convex function; *3*—piecewise linear function; ○—test points; *4*—non-convex function

The type of a priori information (hypothesis) depends on the physical nature of the object (e.g. the fuel consumption of the boiler is known to rise as its load increases) and on the optimization method used. For instance, the algorithms based on the Lagrange optimization technique (see below) require convex characteristics so it is advisable to refer the convexity as the a priori information in approximating the equipment characteristics.

The polynomials of a degree higher than second usually improve the accuracy of approximation and decrease the total standard deviation. However, the resultant curve may be not convex and should be additionally smoothed to permit the use of the Lagrange method. The optimization method allows a straight-forward approximation with ensuring, e.g. a convex curve. However, the straight-forward approximation is more complex and increases the standard deviation. The approximation in the form of a convex curve given by a polyno-

mial of a second degree is close to that given by a higher degree polynomial but differs in the convexity.

Approximation of energy characteristics by piecewise convex functions. To improve the accuracy, the entire working zone of the curve may be divided into two or three segments with describing each of them by a second-degree polynomial.

Consider approximation of the test points of a piecewise convex function each segment of which is given by a second-degree polynomial $B_i = \tilde{a}_i + \tilde{b}_i P_i + \tilde{c}_i P_i^2$, using a dynamic programming method. This method involves automatic selection of the optimal number of segments and the length of each convex zone. The zones are integrated by breaks. Describe the method at greater length.

Approximation with the aid of a two-zone characteristic. The algorithm is based on plotting the approximating characteristic consisting

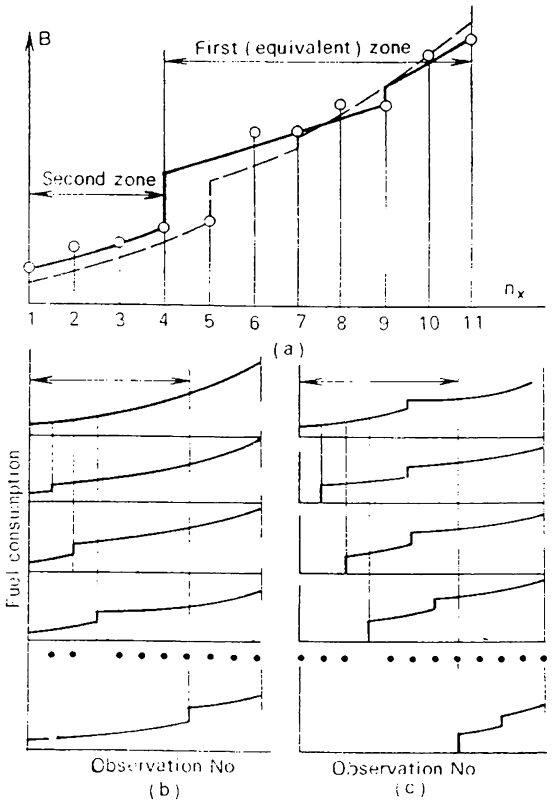


Fig. 7.21. Approximation stages

(*a*) zone numbering; (*b*) plotting of two-zone characteristic ($\gamma_{1-2} = 1$); (*c*) preparation for plotting of three-zone characteristic

of two zones ($l = 2$). Number all the requisite points in increasing order of the value B (present number n_x). Let the last point have number n_k. Number the convex zones in the reverse order counting from the end of the curve to its beginning (Fig. 7.21*a*). The algorithm for plotting the characteristic by dynamic programming includes a direct and a reverse run.

Direct run for $l = 2$. Mark the beginning of the second zone by γ_{1-2} and the boundary between the second and the first zones by r_{1-2}. The maximum number of the test points is n_k. The zone length is characterized by the number of its points. To accelerate plotting, limit the length of the second zone to a maximum of $n_{2.\max}$. Selection of the optimal two-zone characteristic is confined to determining the best position of the boundary point r_{1-2} and the coefficients of approximating polynomials for each zone. The boundary point for the two-zone characteristic is found by the exhaustive search which is performed as follows. Place the beginning of the second zone in the first point $\gamma_{1-2} = 1$ and align the boundary point with point *2*. $r_{1-2} = 2$ (Fig. 7.21*b*). Approximate the first and the second zones separately and find the coefficients of the approximating polynomial for the first zone $\tilde{a}_1$, $\tilde{b}_1$, $\tilde{c}_1$ and for the second zone $\tilde{a}_2$, $\tilde{b}_2$, $\tilde{c}_2$.

The value of the objective function E will also be determined in the course of approximation. The objective function value may be a total standard deviation of the test points from the approximating curve.

The convexity of each segment is checked at each step of approximation. The curve convexity condition at the ith segment is

$$\tilde{c}_i \geqslant 0$$

If the characteristic obtained by approximation is not convex, it is substituted with a linear curve, i.e. if $\tilde{c}_i < 0$, $\tilde{c}_i = 0$ is assumed.

Shift the boundary point r_{1-2} from point *2* to point *3* (one step of scale r_{1-2}) and repeat the procedure (Fig. 7.21*b*). If the objective function diminishes, the shift is justified. Performing this procedure ($n_{2.\max} - 2$) times, i.e. bringing r_{1-2} to the permissible boundary of the second zone, find the only position $r_{1-2} = r_{(1-2).0}$ where the objective function is at the extreme $E_{(1-2).0}$. Memorize this value and the boundary point $r_{(1-2).0}$. The approximating coefficients are not memorized but found repeatedly at the reverse run. Thus, the complete two-zone characteristic is held in the form of three numbers

$$\gamma_{1-2},\ r_{(1-2),0},\ E_{(1-2),0}$$

Shift the beginning of the two-zone characteristic to point *2*, i.e. assume $\gamma_{1-2} = 2$ (Fig. 7.21*c*). Using the above method, find the optimal position of the boundary point $r_{(1-2),0}$, i.e. again determine three numbers $\gamma_{1-2} = 2$, $r_{(1-2),0}$, $E_{(1-2),0}$.

Next shift the beginning of the second segment successively to points *3*, *4*, etc. up to point $n_{2.\max}$ and memorize three numbers γ_{2-1}, $r_{(1-2).0}$, $E_{(1-2).0}$ for each step.

The characteristics thus obtained will be used to plot the curves with more than two zones as illustrated in Figs. 7.21 and 7.22. The plotting algorithm is shown in Fig. 7.23.

To plot a three-zone characteristic ($l = 3$), place the third zone in the beginning of the curve starting from the first point $\gamma_{2-3} = 1$. The continuation of the curve is found among the pre-constructed two-

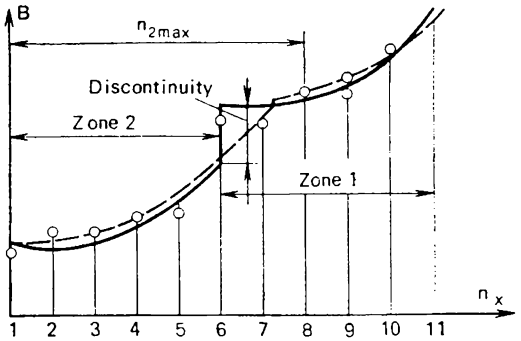


Fig. 7.22. Plotting of three-zone characteristic when changing over from $r_{1-2} = 6$ (solid line) to $r_{1-2} = 7$ (dashed line)

zone equivalent curves. The plotted two-zone equivalent characteristic may be assumed to be the first zone, while the next third zone, the second one. Here resides the essence of using the dynamic programming. The object of each step is to find the boundary between the two zones: a previously plotted equivalent zone and a next zone to be added, i.e. the optimal boundary point $r_{(2-3).0}$. This drastically decreases the extent of exhaustion.

Thus, place the beginning of the third zone in point *1* and the beginning of the equivalent characteristic in point *2*.

It means that a characteristic with parameters $\gamma_{1-2} = 2$, $r_{(1-2).0}$, $E_{(1-2).0}$ is selected from the previously plotted ones and added to them.

The approximation and objective function calculations are performed for each of the three segments. Successively moving the boundary point r_{2-3} to points *3*, *4*, . . . , n_k, we find such a position $r_{(2-3).0}$ whereat $E_{(3-1).0} = \min$ (Fig. 7.21*a*). So the three-segment characteristic is plotted.

Now prepare for plotting a four-zone curve. To this end, successively shift the beginning of the third zone γ_{2-3} to points *2*, *3*, *4*, . . ., $n_{2.\max}$ and using the above procedure find four numbers for

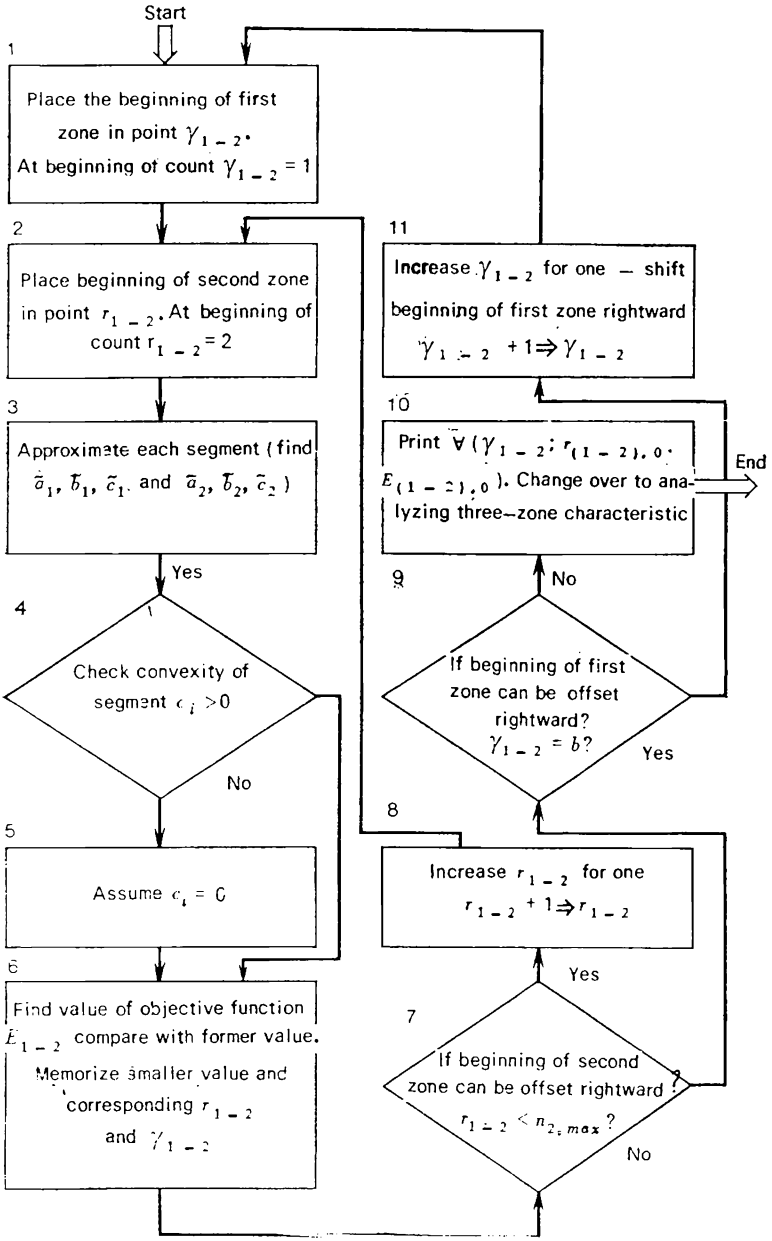

Start
1
Place the beginning of first zone in point γ_{1-2}. At beginning of count $\gamma_{1-2} = 1$
2
Place beginning of second zone in point r_{1-2}. At beginning of count $r_{1-2} = 2$
3
Approximate each segment (find $\tilde{a}_1, \tilde{b}_1, \tilde{c}_1$ and $\tilde{a}_2, \tilde{b}_2, \tilde{c}_2$)
Yes
4
Check convexity of segment $c_i > 0$
No
5
Assume $c_i = 0$
6
Find value of objective function E_{1-2} compare with former value. Memorize smaller value and corresponding r_{1-2} and γ_{1-2}
7
If beginning of second zone can be offset rightward? $r_{1-2} < n_{2,max}$?
Yes
8
Increase r_{1-2} for one $r_{1-2} + 1 \Rightarrow r_{1-2}$
No
9
If beginning of first zone can be offset rightward? $\gamma_{1-2} = b$?
Yes
10
Print $\bar{\gamma}(\gamma_{1-2}; r_{(1-2),0}; E_{(1-2),0})$. Change over to analyzing three-zone characteristic
End
11
Increase γ_{1-2} for one – shift beginning of first zone rightward $\gamma_{1-2} + 1 \Rightarrow \gamma_{1-2}$

Fig. 7.23. Algorithm for plotting equivalent two-zone convex curves in approximating consumption characteristic by dynamic programming

its each position

$$\gamma_{2-3},\ r_{(2-3),0},\ r_{(1-2),\ 0},\ E_{(3-1),\ 0}$$

This is a series of equivalent characteristics of the first zone which in fact comprises three segments. The fourth segment is added to them and the procedure is repeated till l becomes equal to the preset l_{max}, or if no l_{max} is given, till the length of each zone becomes equal to unity, i.e.

$$l_{max} = n_x$$

Reverse run is intended to select the only (optimal) characteristic or a series of fairly good characteristics of all those plotted as above. It resides in transfer from the code of selected characteristic assigned by a collection of boundary points $r_{(j-1,\ j),\ 0}$ and the value of the objective function $E_{(1-j),\ 0}$ to the characteristic per se. For this purpose the least-square approximation is carried out within the limits of each zone (k, $k-1$) and the segment characteristic is plotted

$$B_k = \tilde{a}_k + \tilde{b}_k P + \tilde{c}_k P^2$$

The segments of the approximating function are inteconnected at points $r_{j-1,\ j}$ by a vertical discontinuity. The discontinuity value is automatically found when plotting the general curve. Special programs are prepared to effect this method. An example of approximation is shown in Fig. 7.22. Such a technique is most effective to process the equivalent characteristics of the power plants or systems only if the optimization method used can handle the piecewise convex curves. A special optimization algorithm based on dynamic programming and Lagrange technique is constructed for such characteristics.

Let us consider construction of the piecewise linear approximating function. Such a function can be plotted by the above dynamic programming method assuming that coefficient $\tilde{c}_i$ of each segment is identically equal to zero. However, this method wastes the machine time so that a special simpler algorithm of piecewise linear approximation is developed. If the characteristic is approximated in the piecewise linear form, it is possible to use the algorithms based on the block linear programming which adds greatly to the potentialities of the optimization.

Storage of differential characteristics by computer. The modern methods of the computerized control of power systems are considerably dependent on the organization of storage of the electric and differential characteristics which require large memories. It is sufficient to store the characteristics of one type, e.g. differential. The energy characteristic can be found by integration of the differential one.

The characteristic storage can be organized in different ways, e.g. in the form of the table of unit powers corresponding to a given increment b changing with a constant step Δb. In this case, if b_{max} and b_{min} define the range of Δb, the characteristic of one unit requires

$$k = \frac{b_{max} - b_{min}}{\Delta b} + k_1$$

cells. Here k_1 is a constant equal to 4-8. The characteristics can be stored in the form of an approximating polynomial of the type

$$b_i = \tilde{a}_i + \tilde{b}_i P_i + \tilde{c}_i P_i^2$$

written for each convex zone of the curve. In this case, three cells are needed to store the coefficients and two cells to store the power interval boundaries where the coefficients of polynomial of k_2 numbers hold true. The total number of the required cells is $k_2 n$ where n is the number of zones. The second method is used more frequently and if the power interval is narrow, the incremental rate is sometimes approximated by a straight line or a polynomial of the second or, less often, of the third degree.

7.10. Plotting of Equivalent Characteristics Accounting for Network Power Losses

On many occasions distribution of load between the stations is performed with due regard for active power losses in the electric network. Closely allied to this is the problem of accounting electricity consumed for the own needs when distributing the load between the station units. If a functional relation $\sigma(P)$ can be established between power generation and incremental rates of power losses, the active power losses can be accounted for in the equivalent characteristic with all the values of constant powers. To this end the correction

$$k = \frac{1}{1 - \sigma}$$

is introduced into the characteristic (see Fig. 7.24).

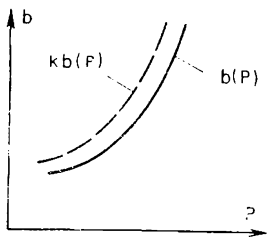


Fig. 7.24. Plant characteristic accounting for network active power losses

The equivalent characteristics for a group of plants are plotted on the basis of the station characteristics accounting for the correction k.

The function $\sigma(P)$ can be obtained only for particular cases as well as the total characteristic of the station recognizing the active power losses.

Finding σ for homogeneous networks. It is known that at separate circuits the active power losses dependent mainly on flow distribution in the electric network are equal to

$$\pi_i = \frac{P_i^2 + Q_i^2}{V_i^2} r_i \tag{7.40}$$

where r = resistance of the electric network circuit
P_i, Q_i = active and reactive power, respectively
V_i = voltage
i = circuit number

Incremental rates of the active power losses

$$\sigma_i = \frac{d\pi}{dP_i} = \frac{2P_i}{V_i^2} r_i \tag{7.41}$$

If the network does not include closed circuits, from Eq. (7.41) one can find the value σ for the plant. For instance with a star net-

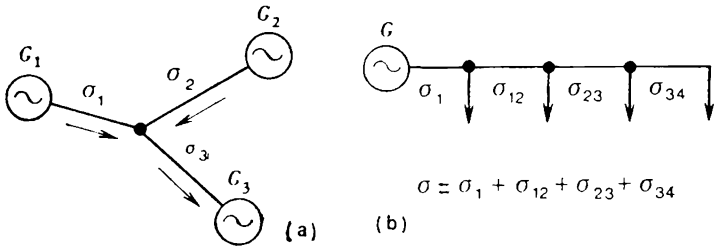


Fig. 7.25. To determination of σ for simple cases

work (Fig. 7.25*a*), power loss incremental rates (PLIR) are found directly from (7.41). For a circuit with a distributed load (Fig. 7.25*b*), plant PLIR

$$\sigma = \sum_i \sigma_i \tag{7.42}$$

where i is the network circuit number.

If the network includes closed circuits, the mutual influence of the active and reactive power distribution can be neglected only for a homogeneous network in which the x_i/r_i ratio is equal for all the circuits since for each closed circuit

$$\sum_i P_i r_i = 0 \tag{7.43}$$

The total value of PLIR of a circuit is proportional to (7.43) so that PLIR for any electric station is equal to the sum of σ_i of the circuits along any path from the plant to the balancing point. Any point of the network can be balancing but it should remain constant

in calculating all the stations. Current at the balancing point is found by the first Kirchhoff's law by vectorial addition of currents at all other nodal points.

Determining PLIR for heterogeneous networks. The total losses of active and reactive powers in the heterogeneous networks take the form of (6.104), (6.105). Assuming that with small changes in the active and reactive powers, the voltage absolute values and phase angles at all the nodal points remain constant, it is possible to derive approximate formulas for calculating σ which have found wide application today. Incremental rates of the active power losses

$$\sigma_p = \frac{\partial \pi}{\partial P_i} = 2 (P_1 B_{i,1} + P_2 B_{i,2} + \ldots) \qquad (7.44)$$

This formula offers a reasonable accuracy and dictates that first coefficients B and then σ are calculated from (7.44) for particular operating conditions of the electric network, then PLIR is found for the circuit between the node of the station to the balancing point i. Such calculations account for PLIR for the particular conditions of the system and plants. If PLIRs are to be allowed for the entire range of the energy characteristics, the calculations are performed anew for each new set of conditions.

Accounting for auxiliary power consumption. On most occasions, the power plant characteristics are plotted with neglecting auxiliary power consumption because it does not exceed 10% and for hydro plants even tenths or hundredths percent. The auxiliary power consumption depends slightly on the operating conditions of the plant and its separate units. Since redistribution of load between hydro units affects but slightly the value of the unit auxiliary power demand, σ_{aux} is usually neglected. On most occasions, the operation of a hydro station is little affected by the total auxiliary power consumption E_{aux}. A detailed analysis performed for the Krasnoyarsk Hydro and Novosibirsk Hydro and for some other hydroelectric stations reveals a substantially nill relation between E_{aux} and E_{HP} (the correlation coefficients vary between 0.2 and 0.3). In case of thermal power units and plants σ_{aux} and power P_{aux} of house turbines are more intimately connected but σ_{aux} seldom exceeds 5%. The value of σ_{aux} for a thermal power plant is easy to calculate separately for the turbine and boiler segments.

Incremental rate for a TPP

$$b = \frac{\Delta B}{\Delta P} = \frac{\Delta B}{\Delta P_b - \Delta P_p} \qquad (7.45)$$

Transform Eq. (7.45) so as to divide auxiliary power P_{aux} into the powers consumed by turbines $P_{aux,T}$ and boilers $P_{aux,B}$ with satisfying the balance

$$\Delta P_{aux} = \Delta P_{aux,T} + \Delta P_{aux,B}$$

then

$$b^* = \frac{\Delta B}{\Delta P_b - \Delta P_{aux,\,T} - \Delta P_{aux,B}} = \frac{b}{1 - \sigma_T - \sigma_B} \tag{7.46}$$

where $\sigma_T = \Delta P_{aux,T}/\Delta P_b$ = incremental rate of turbine auxiliary power

$\sigma_B = \Delta P_{aux,B}/\Delta P_b$ = incremental rate of boiler auxiliary power consumption

ΔP_b = power generated by the unit

Calculations of σ_T and σ_B are performed accounting for cut-in of large electric motors, e.g. of feed pumps, and the relations between $\sigma_T(P)$ and $\sigma_B(P)$. These calculations are labour-consuming and are resorted to only when the load distribution is affected.

8

SELECTION OF POWER SYSTEM UNITS

8.1. Description of Problem

The availability of units in the system determines its economy and reliability. Engagement of certain units affects the value and allocation of the system reserve, operating conditions of the electric network, tie line power flows, fuel consumption of the system, etc. Therefore the problem relates to the most vital ones.

In the general case, for a system comprising m hydro plants and n thermal power stations, the problem consists in finding the requisite units and load distribution between them for each calculated interval of the total optimization period T with a view to minimizing the operation costs and satisfying all the reliability constraints. The problem is affected by the energy characteristics and starting fuel consumption of units, type, grade and cost of fuel, discharge constraints, power losses, electric network constraints, constraints in the combination of units in use, and others.

This problem is non-linear, whole-numbered, multi-extremum, and highly dimensional. If the system plants comprise n units, each of which can be either cut in or cut out, the entire set of variants for any power is 2^n. To find the solution, the planner has to compare a lot of possible variants with optimal distribution of loads between the units.

When the methods and algorithms of optimal distribution of load are well-elaborated (see Chapter 6), the units are still selected by approximation, since the regular body of mathematics used to solve such problems is very complex. To diminish the dimension and simplify the formulation, the problem should be decomposed.

Problem decomposition. Two levels are adopted. The first level is CCD, ACB or RPD. Using approximate and often rough methods, the cut-in power plant units are planned and the equivalent characteristics of the plants and systems are plotted. These characteristics are used to distribute load at all the levels, except the station level. Thus, the load curves are plotted for separate branches of the Power Grid and power plants.

The second level is represented by the power plants. The optimal availability and operation of the station units are chosen to satisfy the given load schedule, i.e. the intra-station optimization problem is solved.

In most cases the above two levels are not interconnected by feedback. At the first level the availability of units is deliberately non-optimal, hence the plant load curves are not very favourable. Theoretically, the problem is solved by iteration. The availability variants determined by intra-station optimization should be used as source data for repeated calculations of the equivalent characteristics with a view to finding the refined load curves and so on. However, the optimal distribution of loads at all levels, plotting of equivalent characteristics and selection of unit availability cannot be integrated into a single whole because of a plurality of organizational, algorithmic and computing difficulties. Therefore, the iteration cycles are usually rejected. To exclude gross errors, the real-time updating of the plant load schedules should be carried out at the power system level, while the unit load curves should be refined at the plant level.

In the general case, the units should be selected with due regard to the active-reactive power balance of the system. The unit availability is determined on the one hand by the active powers of the consumers and power frequency control, on the other hand by the reactive powers of the consumers and voltage regulation in the system. However, it is usually impossible for some reasons to solve the problem as a whole. Firstly, the reactive loads can but hardly be predicted at the power system level. Secondly, the reactive load balances are made up separately for each segment of the system, since transportation of reactive power over great distances is economically unfeasible. On the contrary, the active power balances are made up for the entire system. This difference presents additional calculation problems. Besides, the voltage permissible range is fairly wide ($\pm 5\%$ of the rated value), which may cause errors in selection of the units. In view of the above, when the short-term plan is elaborated, the units are selected only on the basis of the active power balances and requisite frequency control of the system. Next the solution is subject to the real-time refinement. Should the aforementioned solution disturb the voltage regulation conditions, the additional units are committed as required.

The reactive power standby of the power system is to ensure local reactive power balances.

It should be noted that theoretically this problem can be solved as a whole. The most known algorithms for solving the availability problems are discussed in the sections hereinbelow.

8.2. Intra-Station Optimization

The intra-station optimization provides for saving the resource (fuel or water) by selecting the best availabilities, as well as active and reactive powers of the units. It is assumed that the plant operates

with loads assigned by the power system and that all the system constraints are satisfied.

The intra-station problems are particularly vital at the stage of real-time planning and control of plant operation. At the initial stage of real-time planning the unit operation schedule is drawn up. The schedule is based on the forecast and allows the operating personnel to plan measures for rational control of the station for the forthcoming period, usually a day. The second stage involves real-time control. If the current information does not deviate from the forecast, the planned control strategy is realized. If deviation is detected, the schedule is refined. The both stages make up the principal tool for ensuring reliability and feasibility of the system by supplying active loads, regulating frequency and voltage, ensuring dependable connections, trouble-free operation of units and so on. Therefore the problems of intra-station optimization feature a great diversity in system and plant constraints. In case of a system optimization, many plant constraints are neglected, whereas the intra-station optimization requires their detailed analysis and accounting.

Another particular of the intra-station problems is that most control processes are automated so that the solution should allow realization by means of automatics. No matter how complete is the mathematical model, the solution will make no sense if it ignores the potentialities of the dispatch control facilities or logic of the automatic devices.

In the general form the mathematical model includes:

1. Objective equation

for TPP

$$B = \sum_t B_t \Delta\tau_t \Rightarrow \min \tag{8.1}$$

for HP

$$W = \sum_t Q_t \Delta\tau_t \Rightarrow \min \tag{8.2}$$

2. Coupling equation. This represents unit consumption (discharge) characteristics $B_i\ (P_i)$ or $Q_i\ (P_i)$, where i is the unit number.

3. Constraint equations comprising:

(a) balance power equation

$$P_t = \sum_i P_{i,t} \tag{8.3}$$

(b) constraints for active and total powers of units;

(c) constraints for the number of units in use

$$Z_t \geqslant Z_{\min,\ t} \tag{8.4}$$

(d) constraints for combinations of units engaged;

(e) constraints for realization of the solutions, imposed by the process automatic equipment;

(f) constraints for the time of compulsory operation of the units and outage before starting.

These constraints are imposed by the plant electric connection scheme, accident protection, layout of hydro structures, etc.

In these equations B_t, Q_t are consumption of fuel and water during interval t which includes the starting consumption; P_t is the assigned resistive load of the plant; $P_{i.\,t}$ is the active powers of units i during interval t.

APCSs offer strong possibilities for solving the intra-station problems. It is impossible to obtain a correct solution of the problem formulated as above without a computer. Actually, if it is solved using only operation charts and instructions, the dispatcher can rely only upon his experience and skill, whereas the computer allows the use of algorithms and programs.

8.3. Selection of Units in All-Thermal System

In many instances the problem of optimal availability can be interpreted as the problem of committing some additional units or stopping some available units. With such an approach, there is no need for determining the complete availability of the units but only the sequence of connection (disconnection) of the units is to be found, which drastically decreases the dimension of the problem and allows sufficiently rational algorithms to be obtained.

Such a formulation of the problem is most suitable for the real-time control of the system. Really, a problem of complete change of the operating units can never arise in this case even if noticeable economy is predicted. Such an approach is fully rejected by many other facets of the problem. This formulation often leads to a correct solution also when planning operation of the system, e.g. for power-and-heating plants with a complex thermal scheme because of extreme difficulties encountered in selection of its units. The same approach is widely used for condensation plants since the boiler and turbine equipment of thermal plants have large starting consumptions, so that the problem of unit selection is solved on the assumption of deliberate unfeasibility of excessive startings and stoppings.

The problem of outage (operation) of units can be solved by exhaustion but the use of a special outage feasibility criterion is more convenient.

Outage feasibility criterion. The criterion is based on comparison of the unit specific fuel consumption with the incremental rate of fuel consumption in the system and allows selection of a rational sequence

of starting (stopping) of the units without determining the total fuel economy for the system.

Let system load P_t be optimally distributed between the units. The incremental rates of the system and units are b_s. Stop the jth unit with generated power P_j and consumed fuel B_j. Assume that the unit power is small with respect to the power of the system and the outage of the unit does not change incremental rate b_s. Now the available units in use are additionally loaded by P_j and their fuel consumption increases by $\Delta B_s = b_s P_j$.

If $\Delta B_s \leqslant B_j$, the outage of the jth unit is feasible. The boundary of feasibility is $b_s P_j = B_j$. Divide the both sides by P_j and, since specific fuel consumption $b_{sp,\ j} = B_j/P_j$, the outage is feasible if the unit specific fuel consumption is greater than or equal to the incremental rate of the system, i.e.

$$b_{sp,\ j} \geqslant b_s \qquad (8.5)$$

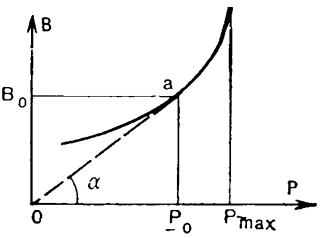


Fig. 8.1. Determination of economy power of unit

The strategy of the outage (starting) of units is determined by the feasibility criterion as follows. It is easy to find the power on the unit consumption characteristic whereat condition (8.5) is satisfied (Fig. 8.1). To this end, trace a tangent from the coordinate origin to the consumption characteristic.

By an interpretation of the derivative, $\tan \alpha = \frac{dB}{dP} = b$, i.e. the slope of the curve is equal to the incremental rate b. On the other hand, $\tan \alpha$ at the same point a is equal to specific fuel consumption, i.e.

$$\tan \alpha = \frac{B}{P} = b_{sp}$$

Thus, the condition $b_s = b_{sp}$ is fulfilled at this point. By selecting points to the right and left of a on the curve, one can see that at a power segment $0\text{-}P_0$ $b_{sp} > b_s$ and with powers from P_0 to P_{max}, $b_{sp} \leqslant b_s$. Thus, criterion (8.5) holds good at powers $P \leqslant P_0$. From here, if the unit power drops to $P \leqslant P_0$, its outage is feasible. The boundary power P_0 is termed an economy power of a unit.

Proceeding from this postulate, it is easy to plan the strategy of cutting out and in of the units when the system load is known. Fig. 8.2 illustrates an example of controlling three units. Let the system initial load be P_1 and the incremental rate be $b_{s,\ 1}$. With the powers distributed optimally, the system balance is $P_1 = P_{1,\ 3} + P_{2,3} + P_{3,3}$. As the system load drops to P_2, the incremental

rate decreases to $b_{s,2}$. Inasmuch as load $P_{3,2}$ is lower than the economy power $P_{e,3}$ of unit *3*, the outage of the latter is feasible. Thus, units *1* and *2* should remain in operation. With a further drop of the load to P_3 at incremental rate $b_{s,1}$, unit *2* should be also cut out.

This simple example reveals the drawbacks of criterion (8.5). Actually, it is derived on the assumption that the unit outage will

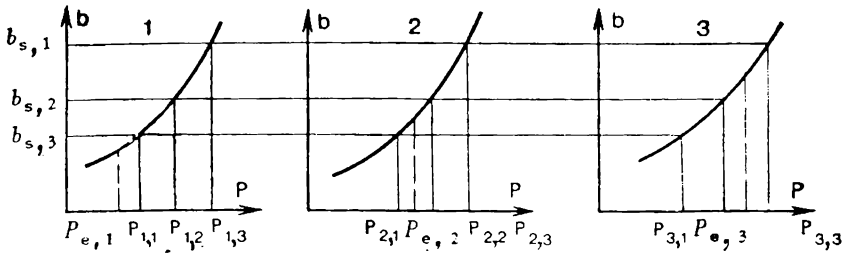


Fig. 8.2. Determination of unit availability using outage feasibility criterion
1-3—characteristics of separate units

not lead to a noticeable change in the incremental rate of the system. For very large power systems this assumption is good, whereas in our example the incremental rate of the system at loads P_2 and P_3 changes sharply, depending on the units in operation. In this case the feasible operation points are offset from the points of economy power $P_{e.1}$, $P_{e,2}$, $P_{e,3}$, which cannot be taken into account beforehand and makes criterion (8.5) still more uncertain.

This drawback can be eliminated by finding the incremental rates as arithmetical means for the initial availability $b_{a,i}$ and final availability $b_{a,f}$ (i.e. without the unit to be cut out)

$$b_{a,m} = \frac{b_{a,i} + b_{a,f}}{2}$$

Now the feasibility criterion is

$$b_{sp,j} \geqslant b_{a,m} \tag{8.6}$$

Substituting (8.6) for (8.5) complicates the algorithm and requires variant calculations. Criteria (8.5) and (8.6) do not account for power losses in the electric networks, whereas variation in the units available may change operating conditions of the system. On most occasions changes in the network power losses cannot exert noticeable effect on the unit availability because of incomparableness of the economic effectiveness from these two problems, however in some cases the influence of the network conditions upon the system unit availability becomes evident. Now the incremental rates of separate

power plants b_i' should take into account incremental rates of network power losses σ_i

$$b_i' = \frac{b_i}{1-\sigma_i}$$

where b_i is the incremental rate of the units.

The general form of the feasibility criterion is

$$b_{sp,\,j} \geqslant \frac{b_{i.\,m}}{1-\sigma_i} \tag{8.7}$$

The condition (8.7) requires the analysis of the electric network conditions and likewise (8.6) offsets the outage feasibility points.

Despite the above-mentioned shortcomings, the conditions (8.5) through (8.7) have found application in availability control algorithms. They are most frequently used at the stage of operation planning. However, their insufficient accuracy puts forward a task of further improvements in the methods and algorithms for optimizing availability of units in the power systems.

Mathematical model of availability optimization problem with using outage (cutting-in) feasibility criterion. Let us consider a particular variant of unit availability and changes of the system fuel consumption resulting from the outage or starting of one of the units. The problem is solved for the all-thermal system. The same procedure is applicable to TPPs with lateral coupling.

Discuss the general model of the problem.

1. The objective equation which determines the economy of outage of the ith unit is

$$B_{e,\,i} = B_0 + \left(\int_{P_{1,\,0}}^{P_{1,\,k}} b_1\, dP + \int_{P_{2,\,0}}^{P_{2,\,k}} b_2\, dP + \ldots \right) - B_i \Rightarrow \min \tag{8.8}$$

The system conditions will be changed because of the outage of the ith unit having consumption B_i. This will redistribute power between the operating units. Now the first unit will operate with power $P_{1,\,k}$ instead of $P_{1,\,0}$, the second unit with power $P_{2,\,k}$ instead of $P_{2,\,0}$, etc.

If the incremental rates correspond to their average value, (8.8) can be written as

$$B_{e,\,i} = B_0 + b_m P - B_i \tag{8.9}$$

where P is the system load; B_0 is the initial (before change of the availability) consumption of fuel.

2. The coupling equations are the consumption characteristics of units B_j (P_j), where j is the unit number.

3. The constraint equations include the power balance equations

$$P = \sum_{k} P_k - P_i - \pi \tag{8.10}$$

where k is the number of the units in operation, $k \in j$; i is the number of the unit to be cut out, $i \in j$. Besides, the constraints to the permissible powers of units or stations are taken into account

$$P_{k,\,\min} \leqslant P_k \leqslant P_{k,\,\max} \tag{8.11}$$

4. The optimization equation is derived to find the optimal strategy for controlling the unit availability. The optimal strategy specifies the rational order (sequence) of outage or starting of the units. Depending on the particular situation, the conditions (8.5), (8.6) or (8.7) can be used.

Selection of the unit outage strategy for a given load schedule in view of starting consumptions. When performing calculations against the given load schedule of the system it may turn out that the unit is cut off for a certain part of the calculated period and then the same or another unit is to be cut in again. In this case the starting consumptions should be taken into account. If starting consumptions B_{st} depend on unit outage time t_{out}, the outage is obviously feasible only when outage fuel economy B_i exceeds the fuel consumption for the subsequent starting, i.e. the following condition is satisfied

$$\int_{t_a}^{t_b} B_i \, dt \geqslant B_{st}(t_{out}) \tag{8.12}$$

where t_a and t_b are the moments of stopping and starting of the unit.

When the starting consumptions are linearly dependent on the unit outage time, the outage is feasible if

$$\int_{t_a}^{t_b} B_i t_{out} \geqslant a t_{out} \tag{8.13}$$

where $t_{out} = t_b - t_a$ is the unit outage time; a is the constant factor.

It is natural that (8.13) is simpler than (8.12) and is therefore more frequently used to solve the problem. The starting consumptions can be allowed for in the outage feasibility criterion by introducing the following correction

$$b_{sp,\,j} \geqslant b_s + \frac{B_{st}}{t_{out} P} \tag{8.14}$$

The addend in the right side of the inequality (8.14) allows for additional fuel consumption to cover the system load, P, stemming

from the starting consumptions. The order of this value corresponds to the dimension of the incremental rate of the system.

Accounting for the starting consumptions offsets the feasible outage conditions towards the lower loads than the economy powers of the unit and rules out the possibility of a unique strategy of availability control. The problem requires iteration for its solution. First, find the unit conditions with neglecting starting consumptions for all the time intervals. Using the data obtained, determine the outage time and refine the cut-out moment by (8.14).

Computational algorithm. Find the required availability and power units without starting consumptions for the constant interval loads P_t (the load curve for the period T is assigned by averaged loads P_t at intervals t). To this end:

(1) take an arbitrary value of the incremental rate and select m units satisfying the criterion, e.g. (8.5);

(2) determine the total power of units at optimal distribution of loads between them. If the given load is equal to the unit powers, the problem is solved. In case of inequality the incremental rate of the system is either increased or decreased. The calculations are repeated till the unit load becomes equal to the powers.

Such calculations are used to plot the outage and operation curves for each unit. With such a curve it is possible to refine the calculations with regard to the starting consumptions.

The starting consumptions are found for each outage interval of all the m units. Using (8.14), a new availability is planned and the starting consumptions are refined again. The availability is finally determined by iteration.

8.4. Intra-Station Optimization of Hydro Plant Operation

Let us consider the intra-station optimization as applied to a hydro plant. The fundamentals of the technique remain effective also for thermal power stations.

The intra-station optimization problem plays an important role with HPs which are generally intended to regulate the load and frequency of the system. This is associated with periodical stoppings and startings of units and redistribution of loads between them. Therefore the detailed algorithms have been synthesized for the intra-station optimization of HPs. These questions have also received adequate attention within the framework of HP APCS.

Decomposition of intra-station optimization problem. Let us briefly consider the decomposition for HP APCS conditions. The decomposition is performed according to the temporal, situational and functional features.

Temporal feature. The problem is solved in two stages: first at the short-term planning stage and then in real-time control. The short-term planning stage involves scheduling the use of the units on the basis of forecasts. In the real-time control, the plan is updated against the current information. The algorithms of these two stages are to meet different requirements. The first stage imposes no restrictions on the algorithm complexity. In the second case the algorithm should ensure quick solution so as to minimize the time of response to the current information. Therefore, the simpler algorithms are realized at the second stage.

Situational feature. The units are to be controlled under normal, emergency, and post-emergency conditions of the system. Naturally, the optimization criteria differ with the situation. If for normal operation the energy resource consumption is the criterion, it is a certain reliability index in emergency. The different criteria self-evidently cause differences in the structures of the intra-station optimization algorithms.

Functional feature. In APCS the computer operates in a multiprogram time-sharing mode, so that the problem of the intra-station optimization is solved in parts, depending on functioning of the entire automated process control system. The problem can be divided into subproblems of standby control, load distribution, unit availability control, etc.

Thus, the problems of intra-station optimization vary greatly as regards their tasks and methodology. This chapter will deal only with the problem of short-term planning of the unit availability and active powers, since other problems are closely linked with the algorithmic structure of the entire process control system and are not a subject of this book.

The intra-station optimization resides in selection of the units (unit numbers) capable of operating both in the generator (GEN) and synchronous condenser (SC) modes, and of their active and reactive powers on condition that the energy resources of the plant are efficiently used. Discuss a problem of the intra-station optimization when the resistive load graph is assigned for the plant. The problem here is to generate the required active power at minimum consumption of the energy resource. This problem is solved by the plant-level (not by the system-level) effectiveness criteria, i.e: the energy resource consumption or the process efficiency.

Problem. Given: resistive load curve $P_j(t)$ for a hydro plant; the available units with vector k_G with $k_G \in M$, where M is the overall set of units. Each unit is represented by its individual energy characteristic $Q_i(P_i, H_i)$, where $i = 1, 2, \ldots, J$ is the unit number, Q_i is the unit water discharge, P_i is the unit power. H_i is the unit head. Also given: starting discharges independent of the outage time; all the constraints for the availability and use of the units.

It is necessary to find the availability and active power of the units at each interval of time of the overall period of planning with accounting for all the minimum outflow constraints of the period under consideration.

The mathematical model of the problem takes the form of the objective equation, i.e. the discharge rate during the optimization period. At optimal solution the discharge is

$$W = \sum_{i=1}^{i=J} \sum_{t=1}^{t=m} Q_{i,t}(P_{i,t})\,\Delta\tau_t + \sum_{i=1}^{i=J} \sum_{t=1}^{t=m} Q_{s,i,t} c_{s,i,t} \Delta\tau_{s,i,t} \Rightarrow \min \quad (8.15)$$

where $t = 1, \ldots, m$ is the number of the calculated time interval with a duration of $\Delta\tau_t$; $i = 1, \ldots, J$ is the unit number from the available set k_G; $Q_{s,i,t}$ are the starting losses; $\Delta\tau_{s,i,t}$ is the duration of the unit starting period; $c_{s,i,t}$ is the number of startings of the ith unit at interval t.

The problem is solved with recognizing the availability and performance constraints of the units and plant. The most common constraints are

(1) plant active power balance constraints

$$P_t = \sum_{i=1}^{i=J} P_{i,t} \quad (8.16)$$

(2) plant active power standby constraints

$$\sum_{i=1}^{i=J} P_{av,i,t} - P_t \geqslant P_{stb,t} \quad (8.17)$$

where $P_{stb,t}$ is the assigned standby; $P_{av,i,t}$ is the available capacity of the unit;

(3) unit permissible power constraints. The permissible limits vary depending on the temperature conditions of the generators, bearings, cavitation phenomena in turbines, vibration level, etc. In short-term planning the constraints are often regarded constant, and hence

$$P_{i,\min} \leqslant P_i \leqslant P_{i,\max} \quad (8.18)$$

(4) availability (or allocation) constraints, e.g. when the reliability of the auxiliary power system necessitates the commitment of some units, or when relay protection remains effective only with a particular number of units operating, or some combinations of the units are prohibited because of the condition of the bed or tail water banks. Such constraints are often imposed by the

main electric connection scheme when the units feed buses of different voltages and

$$P_{\alpha c} > 0 \tag{8.19}$$

where α_c is the vector of the compulsory units and $\alpha_c \in K_G$;

(5) unit number constraints. The number of units in many cases is determined by operation of the system in the pre- and post-emergency situation, e.g. for dividing the station into asynchronous segments. The constraints for the minimum number of the available units take the form

$$Z_t \geqslant Z_{p.t} \tag{8.20}$$

where Z is the number of available units, $Z_{p.t}$ is the permissible number of available units;

(6) unit commitment constraints. These include the constraints for cold standby periods before starting, or continuous operation time dictated by the thrust bearing reliability;

(7) unit starting/stopping constraints over the period of interest;

(8) solution implementation constraints. These are imposed by the automatic circuits and devices. It is known, for instance, that in the existing devices the load is allocated between the units on the basis of either the equal powers or equal passage area of the nozzle.

Other constraints are also possible, depending on the particular conditions.

The problem solution gives a unit commitment program which sets forth utilization of active powers at each interval of the entire term of planning.

8.5. Methods of Optimization of Intra-Station Conditions

All the existing algorithms for optimal operation of the units can be structurally divided into three parts. The first part includes calculations linked with preparation of the source data, e.g. unit characteristics since they are subject to change as a result of unit ageing, and performance variation. The second part covers optimal allocation and operation of the units with the use of a certain mathematical method. The most common methods are dynamic programming (DP), method of branches and boundaries (MBB), and directed exhaustion (DE). This stage usually results in a preliminary program. In the third part the preliminary program is refined and updated by accounting for the constraints that were previously neglected. The loose methods of recognizing the constraints decrease the optimization effectiveness.

Of the above-mentioned methods, DP and MBB are more accurate. At the same time both DP and MBB do not recognize some constraints,

therefore the third part of the algorithm is used to account for the said additional constraints by rather arbitrary trade-off procedures. In this respect DE is more favourable.

Table 8.1

Comparison of Intra-Station Optimization Algorithms

Hydro plant characteristics	Method of calculation	Number of calculated performances	Number of results coinciding with those of DP method				
			water discharge		numer of units	availability	unit load
			total	±0.1%			
Medium-head with 20 turbines	MBB	1000	228	772	966	870	97
	DE	1000	57	943	916	834	0
Medium-head with 10 turbines	MBB	760	178	582	715	633	30
	DE	760	28	742	690	646	0
High-head with 20 turbines	MBB	330	46	284	312	69	53
	DE	330	23	307	291	195	

Table 8.1 gives a comparative estimate of all the hydro optimization methods in treatment here by reference to the solution obtained by DP, since the latter does not put forward any limitations for the type of the consumption characteristics. A comparison reveals that the methods differ in the results obtained, and more radically in the algorithm parameters, such as the calculation time, requisite memory, general estimate. DP requires 2-3 times as large memory as MBB and 3-5 times as large as DE. The time estimates do not favour DP either. The DE algorithm is the quickest. The DP rating becomes still worse if all the constraints are to be accounted for.

Proceeding from these calculations, we may conclude that DP offers higher accuracy and can be used as a reference for comparison of algorithms. Employment of DP for optimization of allocation and operation of the units is greatly dependent on the computer parameters.

Algorithm for DP calculation of intra-station conditions. The algorithm has been synthesized for hydro plants and modular condensation stations. The algorithm is based on the characteristic library and comprises two parts: the first part comprises plotting energy characteristics of the station, the second scheduling allocation (availability) and performance of the units with accounting for constraints throughout the period in treatment. Inasmuch as the first part of the algorithm was highlighted in Chapter 7, now we consider only its second part.

Using the energy characteristics of a plant plotted by dynamic programming, we can determine the allocation and powers of the units for each time interval of the optimization period in question. The first part usually fails to recognize all the constraints, so the second part is intended to refine the solution obtained in the first part. The refinement is usually performed by trading off. For instance, if the available number of units is less than assigned, it is increased in the draft plan. If the power standby constraints are violated, the additional units are committed. To minimize the outage/commitment losses, some units are not stopped or stopped in advance of the draft plan with accounting for the starting losses. Of course, such modifications "depreciate" the plan because the allocation and loads of units are no longer the best. However, the dynamic programming algorithm is used successfully in the absence of constraints or when their impact upon the decision effectiveness can be neglected. The flow chart of the algorithm is shown in Fig. 8.3.

Block 1: find the region of permissible conditions of the plant and plant performance characteristics, i.e. minimum and maximum powers, head (in case of a hydro plant).

Block 2: solve the first part of the problem, i.e. plot the optimal characteristics with the use of dynamic programming.

Block 3: find (for HP) correspondence of the assigned heads H_a to the available calculation characteristics H_c. In case of discrepancy (block *4*), equate the allocation and performance for H_a to one of the solutions for the calculated heads. The head is interpolated with respect to minimum discharge losses. In case of a condensation station, these blocks are omitted.

Likewise the power interpolation is performed (blocks *5* and *6*), if the calculated points of characteristics P_c do not correspond to the powers P_a of the given load curve.

Block 7: determine the allocation and powers of units for the load schedule. This program is called draft, because it does not recognize all the constraints. The draft program is updated (block *8*) to obtain the final results (block *9*).

Algorithms for calculating intra-station conditions using the method of branches and boundaries. The method of branches and boundaries resides in that a set of all possible unit allocations is successively partitioned into subsets. The subsets are compared with each other at a lower boundary of a certain criterion and in further calculations the subsets which deliberately lack the optimal solution are rejected. The optimization process is determined by the method of branching (dividing) the overal set into subsets. Using the adopted scheme of branching, the planner can select the allocation variants and optimize the load distribution for each of them.

The problem is formulated as follows. Given: station load curve, unit consumption characteristics and incremental rate characteristics.

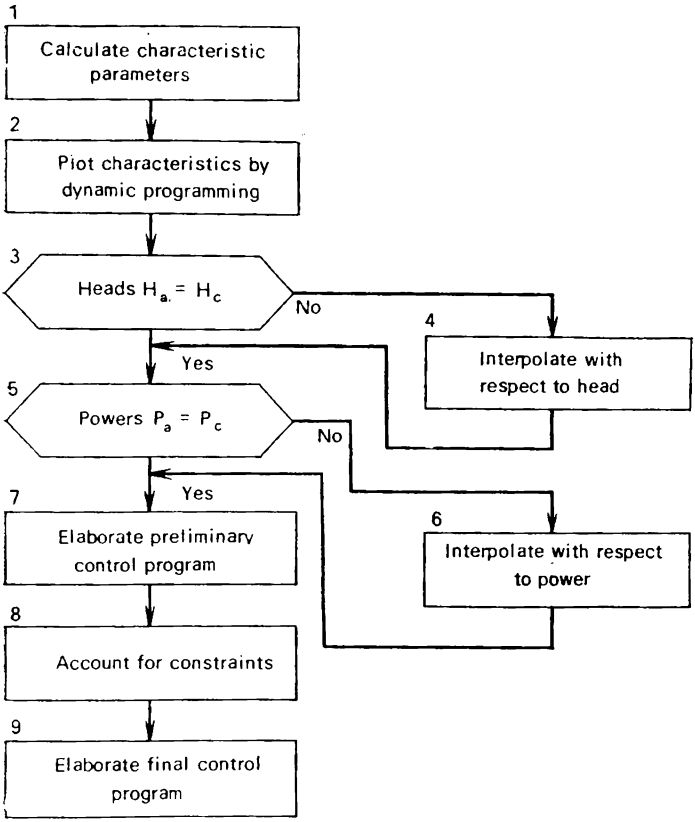


Fig. 8.3. Generalized flow chart of intra-station optimization by dynamic programming

It is necessary for each discrete value of power, e.g. for CP, to minimize the function

$$f(P) = \sum_{i=1}^{i=J} B_i(P_i) \tag{8.21}$$

while observing the power balance and satisfying the power constraints for the available unit.

The unit state is given by vector $\pi = (\pi_1, \pi_2, \ldots, \pi_J)$ each component of which is

$$\pi_i = \begin{cases} 0 \text{ if the } i\text{th unit is off} \\ 1 \text{ if the } i\text{th unit is on} \end{cases}$$

If an allocation is planned and load distribution between units is characterized by vector $\mathbf{P}$ $(P_1, P_2, \ldots, P_J)$, the problem arrives at finding such vector π_o at which

$$f[P(\pi_o)] = \sum_{i=1}^{i=J} B_i(P_i) \Rightarrow \min \tag{8.22}$$

With this technique the subsets are estimated with respect to the lower boundary of criterion (8.22). Meant by the lower boundary is a certain fictitious magnitude. To this end, the consumption characteristic of each unit is replaced with a maximum convex function (Fig. 8.1) for which

$$B_i(P_i) = \begin{cases} \frac{B_{o,i}}{P_{o,i}} P_i \text{ at } 0 \leqslant P_i \leqslant P_{o,i} \\ B_i \text{ at } P_{o,i} < P_i \leqslant P_{i,max} \end{cases} \tag{8.23}$$

where $B_{o,i}$, $P_{o,i}$ are the power and fuel consumption of the ith unit at the maximum efficiency point.

The updated characteristics of the units are used to solve the auxiliary problem of finding the lower boundary of the optimization criterion (8.22) by forming certain allocation variants. The feasibility of the outage is found by the outage feasibility criterion (see Section 8.3).

This intra-station optimization algorithm can be also employed for compiling a draft program of unit control. The program updating in view of constraints is also performed by trading off.

The implementation of this algorithm requires smaller memory and lesser time than the optimization based on DP, which constitutes an advantage of such a technique. However, distribution of load between units by differential characteristics increases the requisite memory capacity allocated for storing the unit characteristics. With a great number of units such an increase may become considerable. Besides, special restrictions are imposed on the type of the unit characteristics, e.g. the differential characteristics should be monotonically rising. In actual practice, this requires artificial correction of the characteristics. The final decision as to the use of MBB is determined by the local conditions.

8.6. Simplified Methods of Hydro Unit Control

The complexity of the intra-station optimization problems, their high dimension, multitudinous constraints, absence of valid source information, etc. in many cases make the use of stringent mathematical methods unfeasible or even impossible. Also of great importance is the fact that the computers used in APCS of power plants are usually capable of handling only fairly simple algorithms. Much work

devoted to the optimization of intra-station operation makes it possible to recommend sufficiently effective algorithms with a reasonable accuracy of solutions. The best way is to regard the overall intra-station optimization problem as a complex of subproblems. Each subproblem recognizes only main decisive factors which simplifies the mathematical models and opens strong possibilities for overcoming computational difficulties.

The simplifications yield best results if they suppress the dimension of the problem. Consider some simplified methods of intra-station optimization applicable in HP APCS.

Let us cite some quantitative indices of the intra-station optimization effectiveness obtained at the existing HPs. Regard the economic effectiveness of optimal allocation of units and load distribution.

Assume that the load can be distributed between the units either by the equal incremental rates, i.e. in the optimal manner, or uniformly. How does the efficiency change in this case? The average losses of efficiency caused by simplified distribution of load amount to 0.3% for the Novosibirsk Hydro, 0.25% for the Gorky Hydro, 0.35% for the Irkutsk Hydro, 0.4% for the Bratsk Hydro and 0.6% for the Mingechaur Hydro. The average values are obtained not for the overall power zone of the station but only for a part thereof corresponding to medium loads. In the maximum load zone, the average value does not exceed 0.2%.

Proper selection of the units gives more vivid results. Let us find the best and worst allocations with respect to efficiency at a uniform distribution of load and determine the difference in the efficiency of HP. The following results are obtained: the Novosibirsk Hydro 0.3-1.2%, the Gorky Hydro 0.3-1.2%, the Bratsk Hydro 0.1-0.3%, the Irkutsk Hydro 0.5-1.5%, the Mingechaur Hydro 0.2-0.5%. The first figure corresponds to the medium load zone, the second to the maximum load zone.

As is seen the number of the available units exerts the most significant effect upon HP efficiency. Assume that the optimal number of the committed units is exceeded by 1, the load is uniformly distributed between them and the allocation is the best. The reduction of the efficiency is given in Table 8.2.

As transpires from Table 8.2, the proper selection of the unit number is far more significant than the optimal distribution of load. This makes it possible to conclude that the optimal number and allocation of the units can be found by using simplified methods of load distribution, e.g. applying uniform distribution of load between the homogeneous units.

In view of the above data it is good policy to divide the unit allocation and performance optimization problem into four independent subproblems: (1) optimal allocation at uniform distribution of load; (2) generating identical solutions for each calculated inter-

Table 8.2

Reduction of HP Efficiency, %, at Non-Optimal Number of Units

Optimal number of units	Novosibirsk Hydro, $H = 16$ m	Irkutsk Hydro, $H = 26$ m	Gorky Hydro, $H = 18$ m	Mingechaur Hydro, $H = 62$ m
2	2.7	—	7.2	4.8
3	1.7	—	2.9	2.9
4	0.6	1.6	1.3	1.5
5	0.5	0.9	1.1	1.4
6	0.45	0.4	1.1	1.0
7	—	0.2	0.7	

val of time and optimization period to minimize the starting/stopping operations; (3) determining the allocation strategy for the optimization period with minimizing the starting/stopping operations; (4) optimal distribution of load between the units.

The first subproblem. This is solved by a directed exhaustion of variants which are formed according to a given criterion. The unit number variants range from minimum Z_{min} to maximum Z_{max} suitable to feed the given load P_j. The number of possible variants Z can be decreased by using a directed search of the best variant. The directed search is organized on the basis of physical laws representative of the production process and allows for successively selecting from the total set of variants only those subsets which probably contain the optimal solution.

Figure 8.4 shows the performance curve of one unit, which is conventionally divided into three zones. In zone *I* increasing the number of units decreases the efficiency of each unit, in zone *II* the efficiency can either increase or decrease and in zone *III* increasing the number of units increases their efficiency. Analyzing the unit performance with respect to zones, we can define the principle of partitioning the overal set of variants. The direction of the search is dictated by the number of units Z_{min}, since in this case the total losses of the unit idling are minimum, while the efficiency is rather high.

The unit number variants are estimated by water discharge rate and the entire set is divided long before the exhaustion.

The best combination of units for optimal number Z_o is selected by comparing the characteristics of the available units at a uniform distribution of load. The objective is to find the optimal combination A_o corresponding to the optimal number of units Z_o to minimize water discharge. To achieve this, the units are ranked according to efficiencies at equal powers.

The first place is given to the unit of the best efficiency, next follow the units in the order of decreasing efficiencies. Naturally, the first Z units of the series determine the optimal allocation. For instance (Fig. 8.5), at $Z = 1$ each unit feeds load $P_{z=1}$ and unit *1* is the best. At $Z = 2$ each unit feeds load $0.5\,P_{z=1}$ and the best are units *2* and *4*, at $Z = 3$ the best are units *2*, *4*, *3* and so on. Comparing water discharges at $Z = 1, 2, 3$ and the above allocations, find the optimal

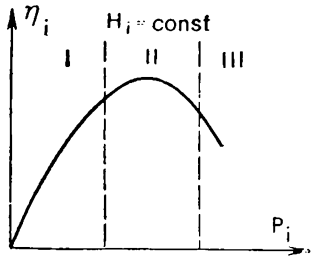


Fig. 8.4. Typical efficiency variation zones on unit performance characteristic

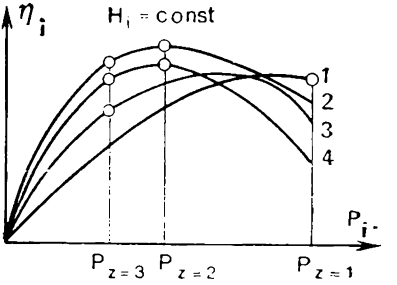


Fig. 8.5. To methods for determining optimal availability at uniform distribution of load

solution to minimize the outflow value. At this stage the unit number and allocation constraints are easily accountable so that only admissible combinations are left for consideration.

The second subproblem. Analysis of unit characteristics of different plants reveals that the difference between the efficiency of units of the same fixed-head hydro station reaches 1-5% and with a constant Z there are several allocations with the efficiency difference not exceeding the permissible limits. Assume these allocations to be equal. The equal allocations give equal strategies of control. The flexibility of the allocation control increases if several strategies are provided. All the strategies are determined from the equal allocation matrix, the rows of which are the allocations and the columns, the numbers of the calculated time intervals.

The directed search of all the equal variants of allocations at Z_0 is carried out by the organized exhaustion of units. To this end, the same ranking of units as in the first subproblem is used. For determining the allocations close to optimal, the worst (last) unit of the best availability corresponding to Z_0 should be replaced with the best (first) of the units in the cold standby.

The equal solution matrix allows finding a number of allocation control strategies.

The third subproblem. The equal solution matrix can be used to find the strategy corresponding to the minimum or permissible number of the starting/stopping operations. If there is no strategies

with a permissible number of starting/stopping operations, it is necessary to refine the strategy with the minimum number of such operations. Such a strategy will naturally involve additional losses of water discharge.

The fourth subproblem. Perform the optimal distribution of load between the units the availability of which was determined by the equality of incremental rates when solving the third subproblem.

As proved by the checks, solving the intra-station optimization problems in parts does not decrease the optimization effectiveness by more than 5%. This algorithm is very convenient to allow for the constraints imposed on the unit availabilities, is very rapid and compatible with the computers included in HP APCS.

8.7. Use of TPP Equivalent Characteristic Library

In the general case TPP can be equipped with boilers and turbines of different types, interconnected by a common steam line. The intra-station problems are still very complicated and have to be solved by simplified methods. One of such methods resides in the use of the characteristic library. Each characteristic is plotted for a particular and constant availability of turbines and boilers. The characteristics plotting of which was discussed in Sec. 7.6 can be used for optimization of the intra-station performance of TPPs.

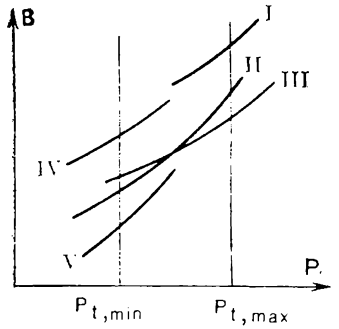


Fig. 8.6. Diagram of TPP characteristic library

The maximum and minimum loads of the plant for the optimization period are determined from the given load schedule. If the library contains characteristics which make it possible to supply the load within the aforesaid range, the optimal allocation is selected from them. Thus, the primal trend is to exclude all the starting/stopping operations for the period in treatment.

The example of library characteristics for constant availabilities *I-V* is shown in Fig. 8.6. The plant can operate without switchings in the range from $P_{t,\,min}$ to $P_{t,\,max}$ only with allocation (availability) *II* and *III*. Comparing fuel consumptions for schedule $P(t)$, finalize the optimal allocation. If there are no optimal variants, use criterion (8.14) and account for the starting consumptions. The problem can include a plurality of variants so that the exhaustion technique is employed. The exhaustion principles are dictated by the local conditions.

When no variants can be found without changing the allocation, the outage feasibility criterion (8.12) is usually resorted to. To this end, select the unit availability ensuring the maximum load $P_{t,\max}$ and minimum fuel consumption within the possible power range, determine the unit (boiler or turbine) to be stopped and decrease the minimum power of the station. Continue such calculations till passing $P_{t,\min}$. The strategy can be determined also proceeding from another power. As a rule, an experient planner easily finds the competitive variants.

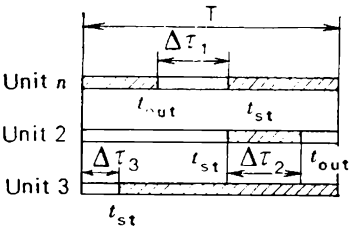


Fig. 8.7. Unit operation diagram for calculating starting consumptions

The need for taking into account the starting consumptions complicates the problem primarily because the notion of "starting consumption" is far broader than simple expenses of energy resource for committing the unit. It also implies the reduction of the equipment and system reliability at startings and stoppings, wear of the equipment, operating conditions, etc. In the light of the above the starting consumption can be estimated only by the test examination, therefore the allocation problems usually recognize only the immediate consumptions for starting the units.

The starting consumptions are taken into account by the agency of the directed exhaustion algorithm. Consider an example of an algorithm for recognizing starting consumption of the units whose operation time charts are shown in Fig. 8.7. The plant operation period includes the down and up times of each unit. For the nth unit the first shown interval lasts from its cut-out time $t_{out,1}$ to the starting time $t_{st,1}$, i.e. $\Delta\tau_1 = t_{st,1} - t_{out,1}$. If the nth unit is run during $\Delta\tau_1$, there will be no starting consumption at the moment $t_{st,1}$ but the operation in the interval $\Delta\tau_1$ will not be optimal and fuel overconsumption will result. For starting consumption linear with time, the consumption increment is

$$\Delta B_n = b_n (t_{st} - t_{out}) - b_n \Delta t_{st} - b_n \Delta t_{out} + \Delta B (\Delta t_{out}) + \Delta B (\Delta t_{st}) \quad (8.24)$$

and the function (8.24) is minimized with respect to variables Δt_{st}, Δt_{out}, which indicate the decrease of the outage period due to a later cut-out Δt_{out} or earlier starting Δt_{st}.

Station incremental rates b_n are found accounting for starting consumptions by (8-14), while the fuel consumption variation function $\Delta B (\Delta t_{out})$ and $\Delta B (\Delta t_{st})$ when optimizing the performance of the station.

This computerized algorithm offers a reasonable computation time.

9

LONG-TERM OPTIMIZATION OF POWER SYSTEM

9.1. Routine Planning of System Operation

The routine planning of the operating systems is essentially the first stage of solving the optimization problems. The main goal of the routine planning is to obtain recommendations for utilizing the energy resources and powers of the system for a period between a month and a year, therefore the optimization problems span accordingly. In the general case the planning comprises the following basic tasks:

(1) find the water resources and optimize their utilization;
(2) find the fuel resources and optimize their consumption;
(3) construct the power and energy balances of the system;
(4) plan major repairs of the power equipment;
(5) determine the technical-and-economic indices of the system and plant operation.

Each of the above problems is the optimization one and to a large measure dictates the economic indices of the system. Multitudinous calculations performed for the real systems show that the long-term optimization problems are usually more effective than some problems of short-term optimization. For instance, optimizing the conditions of water reservoirs allows for increasing hydro power generation by 5-10%, optimizing major repairs cuts repair costs and noticeably increases the available capacities of stations.

At present there are a number of algorithms which are used for solving the long-term optimization problems. Some of them are based on mathematical models employed in short-term optimization, e.g. for constructing the active and reactive power balances of the system, but more frequently they are derived from specially constructed models.

The long-term optimization algorithms are peculiar in the use to some, often considerable, extent of sufficiently vast amounts of statistical data, such as system load history, various indices of plants and systems, hydrographs, etc. This puts forward special requirements for accumulation and processing of statistic information. Another peculiarity is the need for a fairly complete representation of the power system, for instance when solving the fuel supply problem the planner should account for all thermal plants operating on different types and grades of fuel, or the hydraulic coupling

of the chain hydros. Therefore, the mathematical models and algorithms are complex and the computation programs are often executable only on large machines.

Among other features are periodical updatings caused by source data refinement, multistage planning, interrelation of the short- and long-term optimizations, etc. which still more complicate the algorithms and programs. Naturally, rational mathematical models and algorithms for solving these problems are being synthesized at present and it is quite possible that more reasonable technique than proposed in this chapter will appear in the near future.

9.2. Optimization of Water Reservoir Conditions

The principal task of the long-term control of the water reservoir conditions is the optimal utilization of the energy resources of the power system or pool to ensure quality and reliable supply of the assigned loads. With a rational control of the water reservoirs, the hydro power generation can be increased by 1-5%, which yields a considerable economy of fuel.

There are short-term (daily, weekly) and long-term (seasonal, annual and of many years) regulation. The short-term optimization of HP in the system is treated in Sec. 6.3. The optimal operation of HP with long-term regulation is an independent problem which is discussed in this section.

The problem of optimizing the condition of a water reservoir is formulated as follows: with the given domestic inflow, determine such conditions of the reservoir for the entire regulation period whereat optimal, according to the adopted criterion, operation of the power system is ensured. The criterion is usually the minimum operation costs or fuel consumption in the system.

The source information model is initially constructed for the entire period of regulation. The hydrograph, loads and other variables are forecasted. From these data the reservoir conditions are calculated to obtain the initial estimate. As new forecasts are made on the basis of later information, the conditions are updated. The successive updating consists in modifying the hydro plant performance for the planned interval by reference to the forecast for the next interval of optimization. The updating establishes the interrelation between the long-term and short-term operation. The initial interval of updating is usually a month, next is the ten-day period and then comes the daily updating. The successive updatings rely upon multiply repeating optimization calculations which can be performed only on a computer.

In addition to the successive updating technique, the hydro plant operation is optimized with the use of the dispatcher schedules that are the control functions and unambiguously define the hydro performance. The control functions can take different forms, for instance

$Z_{h-w}(t,X)$, i.e. give the reservoir elevation Z_{h-w} for any calendar date t, depending on the value of X. The value of X can represent the domestic inflow, HP average capacity, and other indices pertaining to the past period up to the moment t being considered.

The control functions are obtained after generalizing a large series of reservoir regulation estimates in the determinate formulation, which are representatives of the characteristic conditions. Should the conditions change, the control functions will also change. Thus, both the successive updatings and the control functions require that the problems of optimal operation of HPs in the system be solved in the determinate formulation. Another particular of the task is that the long periods of optimization necessitate elongation of the calculation intervals. It is practically impossible to calculate the annual regulation by hourly intervals. In addition to computational advantages, the enlarged interval calculations are justified by the absence of valid information.

When changing over from the hourly intervals to the daily ones, the planner should account for the effect of the daily variations of the load upon the station indices. If the monthly intervals are the basis for the calculation, it is necessary to take into account the monthly variations, etc. The interval performance is reflected in a specially prepared source information to be used for longer interval calculations. This also contributes to the interrelation between the short- and long-term conditions of HP because the short-term optimization algorithms are utilized for constructing the average interval characteristics of the plants (see Sec. 7.7).

Thus, the problem of rational utilization of HP reservoir water resources is a crucial system-level problem which determines the performance of the system.

Formulation of the problem. Let the system to be optimized consist of J hydro and K thermal power plants. Assume that the source information is determinate for the optimization period. The optimality criterion is represented by system operation costs I_s. The other possible criteria of optimality are the minimum fuel consumption of the system B_f or the maximum hydro power generation E_{HP}. However, the criterion $I_s \Rightarrow \min$ offers the highest accuracy. The criterion $E_{HP} \Rightarrow \max$ is the simplest as there is no need for analyzing system factors and TPP performance when calculating the conditions of the water reservoir. On the other hand, the algorithmic simplification of the problem degrades the accuracy so that the applicability of this criterion is to be checked for each particular case.

The mathematical model comprises the following equations.

1. Objective equation

$$I_s = \sum_{t=1}^{m} c_t B_t (P_{TTP,t}) \Delta\tau_t \Rightarrow \min \tag{9.1}$$

where B (P_{TPP}) is the consumption characteristic of the equivalent thermal power station; c is the fuel unit cost; $t = 1, 2, \ldots, m$ is the number of the calculation interval, $\Delta\tau_t$ long.

Transform (9.1) and complement it with the parameter to characterize the *HP* and reservoir conditions. The power of the jth HP at any instant of time t is determined from

$$P_{HP.j,t} = 9.81\ \eta_{HP,j,t}\, Q_{HP,j,t} H_{HP,j,t} \tag{9.2}$$

and the discharge rate from

$$Q_{HP,j,t} = Q_{d,j,t} \pm Q_{r,j,t} \tag{9.3}$$

i.e. the discharge is derived from domestic inflow $Q_{d,j,t}$ and the regulation outflow $Q_{r,j,t}$ of the reservoir. If the reservoir is filled, $Q_{r,j,t} < 0$ and vice versa, if it is emptied $Q_{r,j,t} > 0$.

At any moment t of period T the power of all TPPs of the system which are to be optimized can be found from the following power balance equation

$$P_{TPP,t} = P_{s,t} - \sum_{j=1}^{J} P_{HP,j,t} + \pi_t \tag{9.4}$$

where $P_{s,t}$ are the given loads of the system, π_t are the network power losses.

Using (9.2)-(9.4), we arrive at the objective equation comprising $Q_{r.j.t}$ which defines the conditions of the reservoir

$$I_s = \sum_{t=1}^{n} c_t B_t \left[P_{s,t} - \sum_{j=1}^{J} 9.81 \eta_{HP,j,t} (Q_{d,j,t} \pm Q_{r,j,t}) \right.$$
$$\left. \times H_{HP,j,t} + \pi_t \right] \Delta\tau_t \Rightarrow \min \tag{9.5}$$

The regulation parameter may be also reservoir discharge $W_{r.j.t}$ and head water elevation $Z_{h-w,j,t}$ which can be easily accounted for in (9.5) by simple manipulations.

2. Coupling equations

(a) power balance equation

$$P_{TPP,t} = P_{s,t} - \sum_{j=1}^{J} P_{HP,j,t} + \pi_t \tag{9.6}$$

(b) discharge balance equation for each hydro plant

$$\sum_{t=1}^{m} W_{t-w,j,t} - \left(\sum_{t=1}^{m} W_{d,j,t} \pm \sum_{t=1}^{m} W_{r,j,t} - \sum_{t=1}^{m} W_{l,j,t} \right) = 0 \tag{9.7}$$

where W_{t-w} is the tail water outflow; W_d is the domestic outflow at dam site; W_l is the outflow losses;

(c) TPP characteristics B_t ($P_{TPP,t}$). These account for the daily variations of the performance (such characteristics are called average daily and their plotting is treated in Sec. 7.7). The TPP equipment availability and typical load schedules usually change during the optimization period, invoking changes in the TPP characteristics;

(d) HP average daily characteristics $Q_{HP,j,t}$ ($P_{HP,j,t}$) which also vary with time t;

(e) tail water and head water characteristics; $Z_{h-w,j}$ ($V_{r,j}$) is the characteristic of relation between the reservoir volume $V_{r,j}$ and head water elevation $Z_{h-w,j}$; $Z_{t-w,j}$ ($Q_{t-w,j}$) is the characteristic of relation between tail water elevations $Z_{t-w,j}$ and discharge rates $Q_{t-w,j}$. These characteristics are necessary for calculating the HP head.

3. Constraint equations

(a) HP and TPP power constraints

$$P_{HP,j,t,\min} \leqslant P_{HP,j,t} \leqslant P_{HP,j,t,\max} \tag{9.8}$$

$$P_{TPP,t,\min} \leqslant P_{TPP,t} \leqslant P_{TPP,t,\max} \tag{9.9}$$

(b) head water and tail water elevations

$$Z_{h-w,j,t,\min} \leqslant Z_{h-w,j,t} \leqslant Z_{h-w,j,t,\max} \tag{9.10}$$

$$Z_{t-w,j,t,\min} \leqslant Z_{t-w,j,t} \leqslant Z_{t-w,j,t,\max} \tag{9.11}$$

For a hydro plant with an annual or seasonal outflow regulation

$$Z_{h-w,j,t,\max} = Z_{NHE},\ Z_{h-w,j,t,\min} = Z_{DVE}$$

where Z_{NHE} and Z_{DVE} are the normal head elevation and dead volume elevation, respectively. The tail water elevation constraints are imposed by the complex utilization of the hydro development water resources.

4. System constraints can be also invoked, for instance the transmission line capacity constraints

$$P_{TL,c,t,\min} \leqslant P_{TL,c,t} \leqslant P_{TL,c,t,\max} \tag{9.12}$$

This is the non-linear programming problem. It is most frequently solved by the following methods: coordinate descent, steepest descent, gradient, etc. A number of algorithms existing to-day provide for solving this problem. Consider one of such algorithms.

The method and the respective programs were developed both for the equivalent fuel minimum consumption criterion and for the maximum hydro power generation criterion. The program allows for optimizing the performance of up to 10 chains and 20 hydro plants with accounting for the demand of the non-generating facilities in the form of the hydro plant operational constraints.

The program calculates the long-term operation of the complex hydro chains by combined optimization of the long- and short-term

performance of the power system. The optimization is carried out in steps. First the optimal long-term operation of HP with due regard for all hydro plant constraints is found with a view to maximizing power production. Next the short-term operation of HPs and TPPs is optimized with respect to the found average interval (average monthly) water discharge rates for each optimization period. The constraints imposed by the transmission line capacity, nodal powers and active power balance in the system for each hour of the day are taken into account. Then are computed the linear polynomials in TPP average interval incremental rates $b_{j,t}$ versus HP monthly discharges $Q_{HP,j,t}$. The characteristics obtained are used for final optimization of the HP long-term operation on the basis of the minimum TPP fuel consumption criterion. If the HP water discharge rates remain inside the linear approximation region of characteristics $b_{j,t}$ $(Q_{HP,j,t})$ after such calculations, the solution is considered optimal as regards minimizing the equivalent fuel consumption. Otherwise the planner should return to the short-term calculations to refine linear relations $b_{j,t}$ $(Q_{HP,j,t})$ for performing on their basis the second additional optimization of the HP long-term operation, and so on.

As we mentioned above, the long-term regulation optimization program is based on a gradient projection method which is a variety of the gradient technique. The method resides in the following.

Assume that the minimum of the convex function is to be found, provided the independent variables satisfy a set of P linear inequality constraints

$$\Phi(X) \Rightarrow \min$$

$$\{AX \leqslant b\} = \left\{ \begin{array}{l} a_{1,1}X_1 + a_{1,2}X_2 + \ldots + a_{1,n}X_n \\ a_{2,1}X_1 + a_{2,2}X_2 + \ldots + a_{2,n}X_n \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ a_{p,1}X_1 + a_{p,2}X_2 + \ldots + a_{p,n}X_n \end{array} \right\}$$

At the initial point X^0 whose phase coordinates satisfy the $AX \leqslant b$ constraint conditions the gradient vector is determined and the motion is performed in the opposite direction (antigradient) behind the boundary of the feasible area to point X^1 (Fig. 9.1)

$$X^1 = X^0 + \alpha_0 \frac{\partial \Phi}{\partial X^0}$$

where α_0 is a certain multiplier which determines the value of the step behind the boundary of the feasible area.

The resulting point X^1 is projected to the constraints $AX \leqslant b$ surface, thus giving point $\widetilde{X}^1$. Next from point $\widetilde{X}^1$ the motion is

performed towards the antigradient, likewise from point X^0, behind the boundary of the feasible area to point X^2

$$X^2 = \tilde{X}^1 + \alpha_1 \frac{\partial \Phi}{\partial \tilde{X}^1}$$

The point X^2 thus obtained is projected onto the constraint surface, thus giving point $\tilde{X}^2$ and so on.

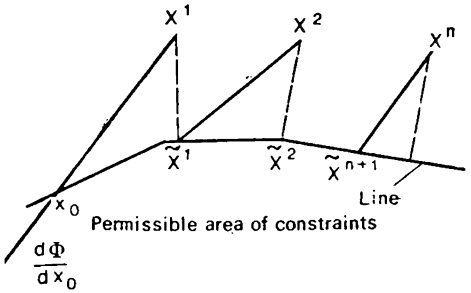


Fig. 9.1. Diagram of accounting for constraints by gradient projection method

If the initial point X^0 is outside the feasible area, it should be first projected to the constraint surface and only after that the above motion can be performed. This allows for solving the problem from any initial approximation.

The equality constraints are accounted for by a specially synthesized projection algorithm which almost fully precludes undesirable oscillations of the iterates around the equality constraint surface.

9.3. Optimization of Water Reservoir Conditions of Isolated Hydro Plant

Let us consider the methods and algorithms for a simpler case in detail. Operation of an isolated hydro plant in the system is a special case, because there are only few power systems which include one isolated hydro plant. However, this example readily demonstrates the particulars of the general problem and the derivation of the optimization equation. The algorithm for the general case is complex and cannot be treated within the framework of this book.

Consider a concentrated system, i.e. a system in which all TPPs are represented by a unique equivalent characteristic. The system includes one hydro station and the task is to find the optimal conditions for its water reservoir.

This problem can be solved by a plurality of algorithms based on different methods of non-linear programming (Gauss-Seidel meth-

od, dynamic programming, etc.). However, since the general problem is usually handled by the gradient methods, we discuss the algorithm for optimization of the isolated HP reservoir conditions with the aid of the said method.

The mathematical model of the problem comprises equations (9.5)-(9.12) but with $j = 1$ and $K = 1$, i.e. for one HP and one equivalent TPP. The optimality criterion is the system fuel consumption: at $B \Rightarrow \min$ the performance is optimal. The regulation parameter is the volume of emptying (filling) of the reservoir, $W_{r.t}$. It can change independently at any optimization interval except the balancing one. At the balancing interval the volume is determined by the discharge balance equation (9.7).

Let the optimization period be divided into $t = 1, 2, \ldots, n$ intervals and n be the balancing one. The independent variable vector is

$$\mathbf{Y}\ (W_{r,1},\ W_{r,2},\ \ldots,\ W_{r,n-1}) \tag{9.13}$$

The vector of the values to be found comprises the HP powers and the reservoir regulation volume within the balancing interval, i.e.

$$\mathbf{X}\ (P_{HP,1},\ P_{HP,2},\ \ldots,\ P_{HP,n},\ W^b_{r,n}) \tag{9.14}$$

As seen from (9.14), $n + 1$ equations are needed to solve the problem. The power balance equations (9.6) give n equations set up for all t intervals. One equation is obtained from the discharge balance by (9.7). Thus the number of unknowns is equal to the number of equations.

Calculation with use of gradient method. Given the objective function $\Phi\ (Y)$ is convex and $\mathbf{Y}\ (Y_1, \ldots, Y_n)$. The gradient technique makes it possible to determine the direction of the most rapid growth of the function, which is the gradient vector direction away from the objective function. Since the function is to be minimized in our problems, the independent variables should be changed in the opposite direction, i.e. in the direction of the antigradient. New values of variables

$$Y_1 = Y_0 + \Delta Y \tag{9.15}$$

where Y_0 is the initial value of the variables, ΔY is the correction to them which depends on the magnitude and direction of the gradient vector.

The variable step is

$$\Delta Y = -h_\alpha \left(\frac{\partial \Phi}{\partial Y}\right)_\alpha \tag{9.16}$$

where h_α is the multiplier which determines the step value, α is the iteration number (particular step h_α is determined at each iteration);

the minus sign indicates that the variable changes in the direction of the antigradient.

The gradient vector is determined by the partial derivatives of the objective functions for all the variables

$$\nabla\Phi = \frac{\partial\Phi}{\partial Y}\left(\frac{\partial\Phi}{\partial Y_1};\ \frac{\partial\Phi}{\partial Y_2};\ \ldots;\ \frac{\partial\Phi}{\partial Y_n}\right) \qquad (9.17)$$

The condition (9.17) dictates that the function Φ be differentiable, i.e. continuous with continuous partial derivatives for all the variables.

The optimization is effected by iteration. The gradient vector is found at the initial point and the parameters Y_0 are changed by

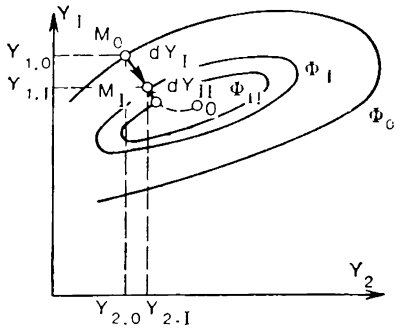


Fig. 9.2. Diagram of gradient method

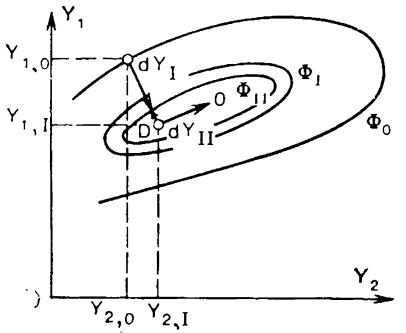


Fig. 9.3. Diagram of steepest descent method

a definite value in the direction to the antigradient. A new value of the gradient vector is determined for new values of Y_{I}, and accordingly a new value Y_{II} and so on till the gradient vector modulus is less than the given value of ε. The performance is regarded optimal (with neglecting the constraints) if

$$|\nabla\Phi| = \sqrt{\left(\frac{\partial\Phi}{\partial Y_1}\right)^2 + \left(\frac{\partial\Phi}{\partial Y_2}\right)^2 + \ldots + \left(\frac{\partial\Phi}{\partial Y_n}\right)^2} \leqslant \varepsilon \qquad (9.18)$$

The iteration usually comprises the steepest descent method. This is characterized by that the motion in the particular direction is continued till the function is minimized. Then the calculation is repeated.

Figure 9.2 illustrates the gradient method as applied for a two-dimension problem; Figure 9.3 shows the steepest descent technique. In Fig. 9.2 the objective function at the initial point M_0 is Φ_0 (the isolines of the objective function constant values are shown). The gradient vector $\nabla\Phi_0$ gives the direction normal to the isoline Φ_0 (it is the perpendicular line where the function features the

quickest rise). New values $Y_{1,I}$, $Y_{2,I}$ will be determined by the step dY_I toward the antigradient. The objective function Φ_I is found at point M_I and thus the correction dY_{II} to variables $Y_{1,I}$, $Y_{2,I}$ is determined. The calculation ends at point *0* where the function Φ is minimized and no changes in the variables can lead to its further decrease.

By the steepest descent method (Fig. 9.3), the step ΔY_I will be made from point M_0 toward the gradient vector $\nabla\Phi_0$, thus giving the minimum function Φ (point D) in this direction. Next the gradient vector $\nabla\Phi_I$ and step dY_{II} at point D are found and so on till the calculation ends at point *0*.

The above description does not show the ways of recognizing the constraints because they have been already discussed.

The gradient method requires calculating a plurality of partial derivatives which, however, presents no particular difficulties in the problem being treated. The advantages of the method are its better convergence than, e.g. of a simpler method of coordinate descent and wider possibilities for taking into account various constraints.

Algorithm for calculating reservoir conditions for isolated HP. First consider the expression for the gradient vector of the function B_F (Y) which depends on the variables Y $(W_{r,1}, W_{r,2}, \ldots, W_{r,n-1})$. The nature of the relation is defined by equation (9.5), but since the value of B_F is the criterion, it is assumed that the fuel cost is constant at all the intervals and hence it can be neglected.

Gradient vector

$$\nabla \mathbf{B}_F = \frac{\partial B_F}{\partial Y} = \left(\frac{\partial B_F}{\partial W_{r,1}} ; \frac{\partial B_F}{\partial W_{r,2}} ; \ldots ; \frac{\partial B_F}{\partial W_{r,n-1}} \right) \qquad (9.19)$$

As transpires from (9.19), to solve the problem it is necessary to determine partial derivatives of the function B_F for all the independent variables. Since the relations between B_F and Y are implicit, each of the partial derivatives can be found by combining other derivatives having explicit relations. For example, the first component of the gradient vector can be written

$$\frac{\partial B_F}{\partial W_{r,1}} = \frac{\partial B_{F,1}}{\partial W_{r,1}} + \sum_{t=2}^{t=n-1} \frac{\partial B_t}{\partial W_{r,1}} + \frac{\partial B^b_{r,n}}{\partial W_{r,1}} \qquad (9.20)$$

The first term of (9.20) shows that if the HP discharge at the first interval is changed by $\partial W_{r,1}$, the system fuel consumption will change for ∂B_1. Changing the discharge at the first interval will change the reservoir elevation and head in the subsequent intervals, i.e. the after-effect will result. The variation of the head will change the HP powers and the fuel consumption in the system. The variation is represented by the second term in (9.20). In the last

nth interval performance will be forced and also dependent on $\partial W_{r,1}$ and previous interval operation.

Assume the components (9.20) to be the derivatives obtained by differentiating the explicit functions. Actually the fuel consumption can change only if the thermal station power varies, which is expressed by the derivative $\frac{\partial B_F}{\partial P_{TPP}}$. The TPP power changes are invoked by the HP power changes, i.e. the derivative will be $\frac{\partial P_{TPP}}{\partial P_{HP}}$. If the network losses are neglected, $\partial P_{TPP} = -\partial P_{HP}$. The HP power is a function of the discharge or head, i.e. $\frac{\partial P_{HP}}{\partial W}$ and $\frac{\partial P_{HP}}{\partial H}$, while the head is a function of the outflow $\frac{\partial H}{\partial W}$. Now the summands of (9.20) can be written

$$\frac{\partial B_{F,1}}{\partial W_{r,1}} = \frac{\partial B_1}{\partial P_{TPP,1}} \frac{\partial P_{TPP,1}}{\partial P_{HP,1}} \frac{\partial P_{HP,1}}{\partial W_{r,1}}$$

$$\frac{\partial B_{F,t}}{\partial W_{r,1}} = \frac{\partial B_{F,t}}{\partial P_{TPP,t}} \frac{\partial P_{TPP,t}}{\partial P_{HP,t}} \frac{\partial P_{HP,t}}{\partial H_t} \frac{\partial H_t}{\partial W_{r,1}}$$

$$\frac{\partial B_n^b}{\partial W_{r,1}} = \frac{\partial B_{F,n}}{\partial W_{r,1}} = \frac{\partial B_n}{\partial P_{TPP,n}} \frac{\partial P_{TPP,n}}{\partial P_{HP,n}} \frac{\partial P_{HP,n}}{\partial W_{r,n}^b} \frac{\partial W_{r,n}^b}{\partial W_{r,1}}$$

All these partial derivatives are readily found by differentiating the energy characteristics $B_F(P_{TPP})$ and $Q_{HP}(P_{HP}, H)$. The exception is derivatives $\frac{\partial H_t}{\partial W_{r,1}}$ and $\frac{\partial W_{r,n}^b}{\partial W_{r,1}}$ for lack of the explicit relation between the head at the interval t and the value of $\partial W_{r,1}$ on the one hand and between the reservoir outflow for the balancing interval $\partial W_{r,n}^b$ and $\partial W_{r,1}$ on the other hand. These relations can be given by approximate analytical expressions.

Outline briefly the optimization procedure. First assign the initial conditions for the reservoir and determine the vector $Y_0(W_{r,1}, \ldots, W_{r,n-1})$. Then calculate the HP operation and if any constraints are violated, solve a special problem for bringing the performance into the feasible area. This problem features many antagonistic constraints which present great computational difficulties. The method of penalty functions offers good results in accounting for the constraints.

In this case the objective function takes the form

$$\Phi = B_F + Pe \Rightarrow \min \tag{9.21}$$

where B_F is the consumption of the equivalent fuel in the system; Pe are the penalty functions. The penalty functions recognize the damage caused by violation of the constraints. Usually $Pe = K(\Delta\Pi)\,\Delta\Pi$, where $\Delta\Pi$ is the value of the constraint infringe-

ment, $K(\Delta\Pi)$ is the estimate function. $K(\Delta\Pi)$ is a non-linear relation.

The value of the penalty for the violation of the constraint for the value of $\Delta\Pi$ is not matched with the actual damage. The damage values are chosen to deliberately exceed the fuel consumption. Now, if the constraint is violated, the function (9.21) rises drastically and the performance turns out unfeasible, therefore the HP conditions are changed to the nearest point where $Pe = 0$.

If the initial conditions were not optimal, then $|\nabla B_F| > \varepsilon$ and the ΔY variable step have to be calculated. One of the possible ways of determining the step resides in the following. Determine the direction of change of each independent variable by the sign of the partial derivative. If the partial derivative is negative and the objective function is to be decreased, increase the reservoir outflow with a step ΔW_r. Should the partial derivative be positive, i.e. the fuel consumption in the system rises, do not increase the outflow but decrease it for ΔW_r during the next iteration.

Calculate the independent variable step

$$\Delta Y = K_h h_0 \frac{\partial B}{\partial Y} \tag{9.22}$$

It depends on the variation of the objective function (9.21) when the independent variables change by ∂W_r, on the initial constant step h_0, on the constant multiplier K_h, the latter being also dependent on the variation of the objective function. If the objective function variations are slight which is indicative of a close-to-optimal solution, the small value of K_h is selected. When the objective function varies considerably, the independent variables can be changed in large steps. There may be several stages for K_h.

The iteration is continued till the modulus of the gradient vector changes by not less than the given value, i.e. the condition $|\nabla B| \leqslant \leqslant \varepsilon$ is observed.

In this algorithm the short-term conditions relate to the long-term ones through the average daily (average interval) characteristics of the stations. If the system includes several hydro plants, the principal structure of the algorithm is not changed, but since the number of the variables and constraint equations increases proportionally to the number of the plants, the size of the problem increases manifold.

9.4. Particulars of Optimizing Cascading Hydro Plants

Cascading plants are typical for utilizing the water resources in the USSR. Unique chains of hydros are in service on the Volga, Dnieper, Angara and other rivers in this country.

The optimization of cascading hydros is characteristic for the power systems and pools. Let us review some particulars of this problem.

When optimizing the conditions of chain reservoirs, the hydraulic couplings (discharge relations) should be taken into account. The chain may include hydro plants with various degree of regulation, which dictates the quantitative and qualitative potentialities of the hydraulic couplings. The hydraulic couplings are weak only when all the cascading stations have reservoirs of many years regulation so that each of them is relatively independent in this respect. The lesser the volumes of the chain reservoirs, the stronger the couplings between the plants, i.e. the discharges of the downstream plants depend on those of the upstream stations.

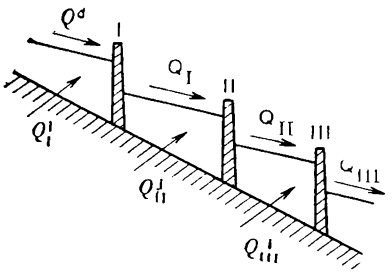


Fig. 9.4. Diagram of cascading HPs

The hydraulic couplings are asynchronous because the river transport delays of discharge between cascading plants amounts to several days. The transport delay time is a function of a broad range of factors, such as the reservoir elevation, inflow, wind speed and direction, water surface conditions (open or closed), etc. All these factors affect the water speed, hence the discharge delay. In case of the Novosibirsk Hydro the discharge wave covers a distance of 200 km for a period from 2 hours to 3 days, depending on the actual conditions. The transport delay time is taken into account in the averaged form which introduces certain errors in the power analysis.

Let us set up the equation for the example chain comprising three hydro plants. We can write the equations of the hydraulic coupling between the upstream and the downstream plants for each optimization interval. These are the equations of couplings between hydro plants *I* and *II*, *II* and *III* (Fig. 9.4). We denote by Q^d the domestic inflow to the dam of the upstream plant, by $Q_{\mathrm{I}}^{\mathrm{i}}$, $Q_{\mathrm{II}}^{\mathrm{i}}$, $Q_{\mathrm{III}}^{\mathrm{i}}$ the inflows to the reservoir of each plant respectively, and by $Q_{\mathrm{I}}^{\mathrm{r}}$, $Q_{\mathrm{II}}^{\mathrm{r}}$, $Q_{\mathrm{III}}^{\mathrm{r}}$ the discharge (filling) of the reservoir of each plant. The discharges are determined with due regard for losses.

The hydraulic coupling equations should be calculated accounting for the discharge transport delay between the upstream plant and the downstream one. The discharge at moment t' of HP *II* depends on the discharge of HP *I* at moment $t = t' - t_{d,\mathrm{II}}$, where $t_{d,\mathrm{II}}$ is the time delay of water discharge between HP *I* and HP *II*. For HP *III* the shift will be similar and $t'' = t' - t_{d,\mathrm{III}}$. Taking

into account the time relation, the discharges for each hydro plant will be

$$Q_{\mathrm{I},t} = Q_{\mathrm{I}}^{d} + Q_{\mathrm{I},t}^{i} + Q_{\mathrm{I},t}^{r} \tag{9.23}$$

$$Q_{\mathrm{II},\,t'} = Q_{\mathrm{I},\,t} + Q_{\mathrm{II},\,t'}^{i} \pm Q_{\mathrm{II},\,t'}^{r} \tag{9.24}$$

$$Q_{\mathrm{III},\,t''} = Q_{\mathrm{II},\,t'} + Q_{\mathrm{III},\,t''}^{i} \pm Q_{\mathrm{III},\,t''}^{r} \tag{9.25}$$

Solving equations (9.23) and (9.24), (9.24) and (9.25) in pairs, we obtain the hydraulic coupling equation

$$Q_{\mathrm{II},\,t'} = Q_{t}^{d} + (Q_{\mathrm{I},\,t}^{i} + Q_{\mathrm{II},\,t'}^{i}) \pm (Q_{\mathrm{I},\,t}^{r} + Q_{\mathrm{II},\,t'}^{r}) \tag{9.26}$$

$$Q_{\mathrm{III},\,t''} = Q_{t}^{d} + (Q_{\mathrm{I},\,t}^{i} + Q_{\mathrm{II},\,t'}^{i} + Q_{\mathrm{III},\,t''}^{i}) \pm (Q_{\mathrm{I},\,t}^{r} + Q_{\mathrm{II},\,t'}^{r} + Q_{\mathrm{III},\,t''}^{r}) \tag{9.27}$$

The hydro stations of the same chain may be included in different power systems. Regulating the hydro plant discharge on the basis of only local system requirements is impermissible. The maximum results can be obtained only if recognizing the requirements for all the hydro stations in complex, which makes the problem being considered most challenging in the engineering, algorithmic and computational respects. The requirements for HP are dictated, among others, by its resources, while the latter can be dependent on the upstream HPs included to a different system. The chain operation can be strongly influenced by the water utility requirements, since the cascades usually serve several purposes. The water utility requirements are set in the form of constraints for discharges and head- or tail-water elevations and may become so significant as to dictate the energy performance of the hydro developments. Finally, the cascading stations are head-related since the tail water of the upstream plant is the head water of the downstream one. Therefore, the discharge of the former and the utilization of the reservoir water resource of the latter affect the head of the upstream plant.

The problem of cascading plant optimization is usually solved at the pool (interconnected system) level. This problem is solved on large computers and requires considerable machine time.

Mathematical model of problem. The size of the problem increases over an isolated HP proportionally to the number of the cascading plants. If the chain includes $j = 1, 2, \ldots, J$ plants, the independent variable vector comprises

$$\mathbf{Y}\,(W_{r,1,1}, \ldots, W_{r,1,n-1}, W_{r,2,1}, \ldots, W_{r,2,n-1}, \ldots, W_{r,J,1}, \ldots \ldots, W_{r,J,n-1}) \tag{9.28}$$

where $W_{r,1,1}$ is the regulated outflow of the first plant at the first optimization interval; $W_{r,1,2}$ is the same for the second interval;

$W_{r,J,1}$ is the same for the Jth plant at the first interval, etc. The number of the optimization interval $t = 1, 2, \ldots, n$, the HP number $j = 1, 2, \ldots, J$.

The mathematical model comprises the following equations

1. Objective equation

$$B = \sum_{k=1}^{K} \sum_{t=1}^{n} B_{F,k,t}(P_{TPP,k,t})\,\Delta\tau_t \Rightarrow \min \tag{9.29}$$

The same equation can be easily written as (9.5).

2. Coupling equations

(a) power balance equations for each interval (n equations in all)

$$P_{s,t} = \sum_{k=1}^{K} P_{TPP,k,t} + \sum_{j=1}^{J} P_{HP,j,t} \tag{9.30}$$

(b) discharge balance equations for each HP for the entire optimization period (J equations in all) are similar to Eq. (9.7).

(c) hydraulic coupling equations for two coupled HPs at each time interval [$(J - 1)\,n$ equations in all]

$$Q_{p,t} = Q_{(p+1),(t+t_d)} \tag{9.31}$$

where t_d is the discharge transport delay between the pth and the $(p + 1)$th plants;

(d) average daily characteristics $B_{k,t}(P_{TPP,k,t})$ of k TPPs;

(e) average daily characteristics $Q_{HP,j,t}(P_{HP,j,t})$ of each hydro plant;

(f) head-water and tail-water characteristics of HPs.

For the head water are given the reservoir volume curves in view of the dynamic capacity of the form $Z_{h-w,j}(V_j, Q_{HP,j-1})$. For the tail water the coupling curves recognize the head

$$Z_{t-w,j}(Q_{t-w,j}, Z_{h-w,j-1}) \tag{9.32}$$

3. Constraint equations

(a) TPP power constraints (9.9);

(b) HP power constraints (9.10);

(c) head- and tail-water elevation (9.11) and (9.12).

In the problem the power of each HP and TPP for each time interval is determined; the unknowns also include the discharge in the balance interval of each HP and hence the vector of unknown values X [$P_{HP,j,t}$, $P_{TPP,k,t}$, W_j^d] and the latter has $n(J + K) + J$ unknowns.

9.5. Optimal Utilization of Water Resources on Multipurpose Hydro Developments

The hydro developments are usually multipurpose and when the water resources are jointly used by different branches of the national economy, the optimization can be no longer performed on the basis of satisfying the needs of only one of them, e.g. the power industry. There are two most typical problems of complex utilization of water resources.

The first problem is optimal distribution of water resources between the hydro development facilities to minimize the operation costs of the water utilization scheme, i.e.

$$E_S = E_O(W_{HP}) + \sum_i E_{w.u,i}(W_{HP}) \Rightarrow \min \tag{9.33}$$

where $E_O(W_{HP})$ are the operation costs of power installations affected by the volume of the water resource utilized; $E_{w.u.i}(W_{HP})$ are the operation costs of the ith water utilization branch.

The second problem is the optimization of the rated parameters of water resource regulation (elevations, discharges, volume of water). The criterion is also the operation costs linked with parameter $P_{w.u}$, i.e.

$$E_S = E_O(P_{w.u}) + \sum_i E_{w.u.i}(P_{w.u}) \tag{9.34}$$

Under the conditions of varying hydrological, technical and economic information, these two problems arise very often. The departmental approach to their solution may inflict a great detriment. At present the second problem is solved by the short-term optimization algorithms and the first problem by the long-term optimization algorithms. The parameters of the complex utilization are restricted by the equality and inequality constraints which should be necessarily satisfied. The constraint size is determined incidentally and a lot of works show that the results are not always objective.

The problem of optimizing the operation of the multipurpose hydro developments has not yet been solved for the general case. There is not a system or pool that would solve it systematically as an operational task. This problem usually arises under extreme conditions and is handled specially. However, the recent changes in the treatment of the environmental control are likely to advance this problem to the most crucial endeavours. We discuss the problem by way of examples.

The Volga complex of hydro developments is intended to serve the needs of the power industry, agriculture, river transport, fish breeding, water quality and flooding control. The requirements of

these branches are often antagonistic. The power industry prefers to utilize the water resources in winter, the agriculture in summer, the river transport in spring, summer and autumn, etc. These contradictory demands can be satisfied to some extent by temporal regulation with the use of comparatively large water reservoirs of the hydro developments. At the Volga Hydro the drawdowns to the tail water are dictated in summer by the fish breeding and agricultural considerations and affect the hatching effectiveness till fishes gain the marketable size (three to four years). The cascade of Volga hydros stores floodwaters, substantially diminishes the maximum outflow to the lower part of the river and hence can dewater some spawning areas. On the other hand, emptying the reservoirs of the chain will be detrimental to the power industry. This necessitates determining the optimal drawdowns in the Lower Volga.

Another example is the energy and transport utilization of the Siberian Hydros. The increased navigation drawdown to the tail water in the autumn-summer period empties the reservoir before the system winter load period and overconsumption of fuel in the power systems. The river transport expenses are made up by the en-route operations depending on the discharge rates throughout the route and fleet operation costs. The calculations performed for three hydro plants have revealed that the optimal solution cuts the operation costs of the power systems and increases the part of the hydro generation to meet the system peaks.

9.6. Optimization of Fuel Supply

The goal is to determine the requisite fuel resources of separate plants, when the power system generates both electricity and heat. The fuel can be of different types (petroleum, gas, coal, etc.) and each type can be of different grades. The fuel distribution depends on the distribution of the electric power and heat energy in the system, transportation costs, fuel depot reserves at the station and many other factors. One of the mathematical models for solving this problem has been developed in the USSR.

The model allows for elaborating quarterly plans of power generation by the plants, the requisite fuel supplies and fuel reserves at each plant at the end of each quarter. The principal objective thereby achieved is the optimal distribution of the allocated fuel funds accounting for the depot reserves between the power plants and determination of the required fuel resources to fulfil the electricity and heat generation schedule. The optimality criterion is the minimum consumption of equivalent fuel in the system.

The problem is developed for the USSR power grid level. The power grid is divided into the generation nodes comprising different power plants. Each node may include several concentrated power

systems, each being represented by its equivalent characteristic. The concentrated systems are interconnected by a network whose power losses and transfer constraints are taken into account. Thermal power plants of each node operating on the same fuel are equivalentized. It is taken into account that the plants can burn equivalent types of fuel (up to 20 types). The performance of NPPs, HPs, thermal loads of TPPs, power consumption by nodes and by the entire power grid, and all the necessary characteristics are given.

Mathematical model of the problem.

1. Objective equation

$$B_\Sigma = \sum_{i=1}^{n} \sum_{\nu=1}^{k} \sum_{t=1}^{l} B_{i,\nu,t} \Rightarrow \min \tag{9.35}$$

where B_Σ is the total consumption of equivalent fuel for supplying electricity and heat for the planned period within the framework of the Ministry of Power Industry of the USSR; $B_{i,\nu,t}$ is the total consumption of equivalent fuel for supplying electricity and heat by the ith power plant on the νth type of fuel during the tth time interval (quarter, year); $i = 1, 2, \ldots, n$ is the number of the equivalent thermal plant; $\nu = 1, 2, \ldots, k$ is the number of the equivalent type of fuel; $t = 1, 2, \ldots, l$ is the number of the time interval.

After developing the objective equation becomes

$$F = \sum_{i=1}^{n} \sum_{\nu=1}^{k} \sum_{t=1}^{l} B_{i,\nu,t} = \sum_{i=1}^{n} \sum_{t=1}^{l} (b_{sp,i,t} E_{i,t} + b_{sp,i,t,Q} Q_{i,t})$$

$$= \sum_{i=1}^{n} \sum_{t=1}^{l} \left(\sum_{\nu=1}^{k} \beta_{i,t,\nu} b_{sp,i,t,\nu} E_{i,t}^{\Sigma} + b_{sp,i,t,Q} Q_{i,t} \right) \Rightarrow \min \tag{9.36}$$

where $\beta_{i,t,\nu}$ is the share of electricity generated on the νth type of fuel in the total generation of the ith installation at the tth calculated interval; $Q_{i,t}$ is the supply of heat by the ith installation at the tth interval; $E_{i,t}^{\Sigma}$ is the total generation of electricity by the ith installation on all types of fuel used; $b_{sp.i.t.Q}$ and $b_{sp,i,t,\nu}$ are the specific consumptions of fuel for heat and power supply for the ith installation at the tth interval of time.

The independent variables are the minimum and maximum values of the equivalent plant powers for each of the equivalent type of fuel and the amount of each type of fuel delivered to the depots. By varying powers, it is possible to change the plant performance within the assigned load schedule of the system, whereas by varying fuel delivery it is possible to optimize the distribution of the system fuel resources.

2. Coupling equations. The equivalent characteristics of nodes show the relation between the nodal power and the required type of fuel. The fuel consumption is estimated in equivalent units.

3. Constraint equation. The problem recognizes a lot of constraints which are only listed here with brief explanation:

(a) power supply and maximum powers of stations;

(b) energy balance in PG;

(c) power balance in PG;

(d) inter-system power flows;

(e) fulfillment of electricity and heat supply schedule;

(f) delivery of fuel from assigned deposits; the matrix is given for the possible deposits for supply of fuel to the plants burning the vth type of fuel;

(g) delivery of deficit fuel; to account for the fuel market condition, the constraints are imposed for limiting its use at a given time interval;

(h) fuel depot capacity; the fuel reserve should not be less than a safety margin or more than the depot capacity;

(i) fuel reserves for the end of the planned period;

(j) delivery of fuel from a particular deposit; the deliveries should not exceed the limit capacity of the deposit;

(k) potentialities of the power plant handling equipment;

(l) fuel balance for the planned year; the allocated resources and the fuel demands are to be balanced.

4. Optimization equation. One of the varieties of the gradient projection method (see Sec. 9.2) is used for optimizing.

Objective function. First arbitrary independent variables are assigned and then these are changed towards the decrease of the objective function by successive iterations. Each iteration gives the objective function and its derivatives on the basis of the independent variables.

The program allows solution of the problem for a system comprising 150 equivalent installations. 30 electric nodes, 20 controlled transmission lines, 25 alternate types of fuel. It includes 12 intervals. The total number of the independent variables in each interval may reach 600, while the total number of the fuel sources should not exceed 120.

9.7. Long-Term Planning of System Power Balance and Power Generation

Various assumptions are used in the long-term planning of system power balances because it is impossible to reliably determine many of the operational variables. The practitioners often develop calculation techniques of their own, which is best suited for the particular system. Such techniques are usually based on the heuristics. However, there exist to some extent universal algorithms which rely upon the philosophy and procedures of the short-term optimi-

zation. These algorithms are computerized and have practical significance.

Two main modifications of the algorithm are constructed. The first calculates the conditions by the characteristic daily load schedules, the second solely by the distribution of load between the stations of the system. The examples of these two algorithms will be discussed in Sections 9.7 and 9.8.

Long-term optimization of system power balances by typical load schedules. Consider a power system including a hydro plant (HP), a power-and-heating plant (PHP) and a condensation power plant (CPP). The task is to plan the availability and performance of the units according to the typical load schedules and determine the fuel consumption of the system. It is possible to optimize all the plants simultaneously with the use of the daily optimization algorithms, however with gross errors in the source information such an approach is seldom justified. The precision of the calculation methods contradicts the inaccuracy of the source data, so that some simplifications can be used.

When optimizing long-term operation of a power system, the HP power generation is assigned for the particular water regime (usually for the average conditions). Taking into account gross errors in forecasting HP power generation (the year may be droughty or rainy) and high efficiency of hydro stations, the assumption is made of the possibility to use approximate methods of distributing load between HPs and TPPs of the system, i.e. the so-called integral load curve (ILC) is employed.

The performance of PHP depends mainly on the thermal loads which are also uncertain under the conditions of a year forecast. Therefore we can use the rated characteristics of specific fuel consumption for the PHP power generation, and hence omit the unit allocation problem. The rated characteristic reflects the requirements to the system operation and allows elaboration of long-term plans.

The availability of units on CPP can be determined with the aid of the characteristic library compiled by the agency of optimization methods.

In view of the above, the problem is formulated as follows: determine operating conditions for the system plants and allocate the CPP equipment to minimize the fuel consumption in the system with satisfying all the constraints. The mathematical model takes the following form.

1. Objective equation

$$B_s = \sum_t B_{s,\,t}(\varphi_{HP,\,t},\ \varphi_{PHP,\,t},\ \varphi_{CPP,\,t}) \Rightarrow \min \qquad (9.37)$$

where $\varphi_{HP,t}$, $\varphi_{PHP,t}$, $\varphi_{CPP,t}$ are the vectors of the operating variables of HP, PHP and CPP, respectively.

2. Coupling equations

(a) consumption characteristics $B_s(P_s)$ of CPP presented in the library and given for different availabilities of the equipment;

(b) characteristics of specific rated fuel consumptions for power generation $b_{sp.j}(P_j)$ for all PHPs of the system.

3. Constraint equations

(a) power balance equations

$$P_{s,t} = \sum_i P_{HP,i,t} + \sum_j P_{PHP,j,t} + \sum_d P_{CPP,d,t} \pm P_{f,t} \quad (9.38)$$

where i, j, d are the numbers of HP, PHP, CPP, respectively; $P_{f.t}$ is the power flow from the adjacent systems;

(b) standby power condition

$$P_{st} \leqslant \left(\sum_i P_{HP,p,i,t} + \sum_j P_{PHP,p,j,t} + \sum_d P_{CPP,p,d,t}\right) - P_{s,t} \quad (9.39)$$

where $P_{HP,p,i,t}$, $P_{PHP,p,j,t}$, $P_{CPP,p,d,t}$ are the available capacities of the plants;

(c) plant permissible power constraints;

(d) constraints for average interval and base generation of HP

$$E_{HP,i,t} = E_{HP,i,t,a} \quad (9.40)$$

$$E^b_{HP,i,t} = E^b_{HP,i,t,a} \quad (9.41)$$

where $E_{HP.i.t}$, $E_{HP,i.t,a}$ are the planned and assigned average interval generation by the ith HP at the tth interval of time; $E^b_{HP,i,t}$, $E^b_{HP,i.t,a}$ are the base generation determined by the water utilization requirements;

(e) PHP thermal load constraints

$$Q_{PHP,j,t} = Q_{PHP,j,t,a} \quad (9.42)$$

where $Q_{PHP,j.t}$, $Q_{PHP,j,t,a}$ are the planned and assigned thermal loads of the jth PHP at the tth interval of time.

4. The optimization equation represents the choice of the best CPP characteristics from the library, the plotting of the equivalent characteristic for a group of plants, determination of the forced operation of PHP and load distribution between HPs and TPPs of the system by the simplified methods.

The problem is solved by solving the interrelated set of subproblems.

The first subproblem is finding the HP performance. It is assumed that HP in the system balance tends to the maximum replacement of PHP generation. The hydro plants are used mainly as the system

peakers and their powers are so selected as to minimize the thermal generation. Figure 9.5 shows the integral load curve employed for the purpose. This method gives a good account of itself when applied to a group of HPs.

The peak load is supplied by the generation of each ith HP

$$E^{p}_{HP,i,t} = E_{HP,i,t,a} - E^{b}_{HP,i,t,a}$$

while the base load, by generation $E^{b}_{HP,i,t,a}$.

Next the constraints (9.40) and (9.41) are checked. This method is very simple but of course inaccurate. For instance, system TPPs may have an excessively broad power regulation range (from minimum to maximum), which may necessitate reallocation of the equipment, the network power losses are neglected, etc. However, on many occasions this technique offers reasonable accuracy and is of practical significance.

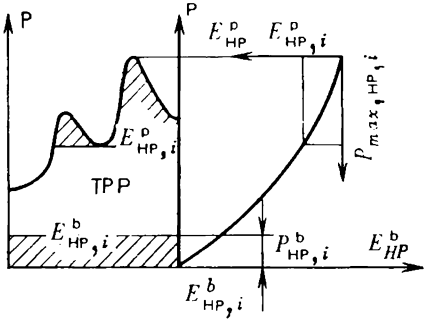


Fig. 9.5. Determination of HP operating conditions by integral load curve

The second subproblem is determining the power schedule and indices of PHP in constrained operation. The base and regulating power are calculated. The base power is induced, it is dictated by thermal loads according to (9.42). The condensing power of PHP can be used as regulating, therefore the rated characteristics of generation fuel consumption are assigned for it. The characteristics are linearized with the use of a linear model, and the total equivalent characteristic of the PHP regulating power is plotted. Using the total equivalent characteristic, one can easily obtain recommendations for scheduling the regulating powers of separate plants.

The third subproblem is finding the performance of CPP. The problem is regarded as the intra-station one. The CPP load schedules are given and from the library only such characteristics are first selected which do not cause reallocations during the optimization period. If the library does not contain such characteristics, the characteristics with reallocations are chosen a priori. The CPP load schedules are assigned heuristically.

The fourth subproblem is distributing the load between the thermal power plants of the system. The equivalent characteristic of all CPPs is plotted using dynamic programming or Lagrange multipliers. Only if the power of all CPPs is insufficient for balancing the system, the PHP regulating power is switched on, the sequence of PHP loading being determined by the equivalent characteristic.

If necessary, the subproblems can be complemented with a subproblem of plotting the HP equivalent characteristic, e.g. by the dynamic programming algorithm. This necessity may arise when the HP efficiency changes widely within the time intervals in treatment.

The equivalent characteristic of HP may also prove requisite during calculating the operating conditions of the system when the subproblem of distributing power between hydro and thermal power plants with due regard for the HP outflow integral constraints arises.

The typical daily schedules of the system load are employed for calculating power generation and fuel consumption by different plants.

9.8. Optimal Scheduling of Power Equipment Repairs

Organization of repairs. Maintenance of the power equipment plays an important role in uninterrupted and economic power supply. It is intended to maintain the equipment available with ensuring the nominal power and performance. The repairs are characterized by a high labour input (more than one half the operating personnel belongs to the maintenance services and enterprises), high costs, and material consumption.

Maintenance includes major, routine and medium repairs. The major repair involves replacement of large and expensive components, overall inspection of the unit condition, analysis of the cause of damage, tests of boiler metal parts. Major repairs can be accompanied by partial modernization of the equipment. The routine repair is intended to keep the equipment available between major repairs. It includes disassembly, inspection and cleaning of units, repair and replacement of parts, adjustment and tests. To upkeep the unit between major repairs (this period is usually called TBO which stands for time between overhauls), medium or broadened routine repair is carried out.

Organization of repairs begins with compiling the optimal maintenance schedule. The schedule is compiled at the hierarchic control levels of PG, ACB, PS. The outage of a unit changes the unit availability, which affects the specific consumption of fuel during the repair period. The unit performance is improved after the repair, owing to the clean heating surfaces, absence of blow-holes and loosened joints, improved performance of the auxiliary units, eliminated (decreased) discrepancy between the available and installed capacities of the unit. All these economize fuel after commitment of the repaired unit.

Mathematical model. Let us consider the mathematical model required to optimize maintenance of the equipment.

1. The objective function for optimizing the maintenance schedule is represented by the reduced costs C_i. In case of the ith variant of the maintenance schedule

$$C_i = E_n (\Delta O_{r.f,i} + \Delta S_i) + \Delta E_{c,i} + \Delta E_{o,i} + \Delta E_{r,i} \qquad (9.43)$$

where $\Delta O_{r.f}$ are the additional outlays for expanding the repair facilities required for a given variant of repair; ΔS is the increase of the circulating capital by laying in a stock of parts, material, etc.; $\Delta E_{c,i}$ is the current expenses for organization and accomplishment of repair; ΔE_r and ΔE_o are the variations of the fuel expenses in the power system during the repair and first year of operation respectively.

The variants under comparison should be equivalent as regards the repair quality (the post-repair availability factor and improvement of the energy characteristic of the unit). This means that the variation of fuel consumption in the post-repair period, i.e. value ΔE_o, can be neglected, if the down periods are equal in both variants. The expression in brackets and the value of ΔE_c can be also considered equal for all the variants of repair.

In view of the above, the optimal maintenance schedule should ensure that the total down-time variation of the fuel consumption caused by changes in the equipment availability be minimized

$$\sum_{t=1}^{t_k} \sum_{i=1}^{n_r} \Delta E_{r,\,i,\,t} \Rightarrow \min \qquad (9.44)$$

The values of fuel consumption are summed up for all the t_k intervals of the repair period and all the n_r units planned for repair in this year

$$\sum^{t_k} \sum^{n_r} c_i \Delta B_{i,\,t} \Rightarrow \min \qquad (9.45)$$

2. The characteristics of the plant in such a model are the absolute or differential energy characteristics of both the available and the unavailable units

$$B_i (P_i); \qquad \forall i \in n$$

3. The repair optimization constraints are fairly numerous but already familiar to us:

(a) by power balance

$$\Sigma P_{av} - \Sigma P_r \geqslant P_t + \Delta P_n + R \qquad (9.46)$$

(b) by permissible performance of all the n available units

$$P_{i,\min} \leqslant P_i \leqslant P_{i,\max}; \qquad \forall i \in n \qquad (9.47)$$

or

$$P_i = 0$$

Additionally the constraints are accounted for in the permissible and impermissible combinations of the units to be repaired simultaneously, repair depot capacity and manpower, etc.

Load curve valley. Prior to searching the optimal maintenance schedule, make sure that load curve valley is sufficient to accommodate the repair area, S_r. To this end, check the condition

$$S_r \geqslant \frac{\sum_{i=1}^{n_r} P_i t_{r,\,i}}{k_v} \tag{9.48}$$

where t_r is the rated time of repair; $k_v = 0.85$ is the coefficient of utilization of the valley area.

To estimate the duration of the major repair $t_{m.r}$ in days, use can be made of the data on the average annual rated down time at overhaul of different units listed below:

Hydraulic units	15
Units of TPPs with lateral couplings	15
TPP units:	
up to 210 MW	18
300 MW	24
500-800 MW	30
1200 MW	36
NPPs	45

Bear in mind that the actual rated duration of the repair is obtained by multiplying $t_{m.r}$ by the TBO value (four years for hydraulic units and TPP units up to 210 MW in capacity and three years for other units). Thus in case of 300-MW units

$$t_r = t_{m.r} T_{TBO} = 24 \times 3 = 72 \text{ days}$$

Feasible outage procedure. We recall that the outage feasibility condition is written as the equation of the relative incremental rate of fuel consumption by the power system and the specific minimum fuel consumption by the unit (according to the fuel cost) and takes the form

$$c_s b_s = c_i b_{sp,\,0,\,i} \quad \text{or} \quad b_{sp,\,0,\,i} = \frac{c_s}{c_i} b_s$$

Now, if $c_i b_{sp,\,i} > b_s c_s$, the outage is feasible as giving fuel economy.

In the list of units planned for repair, $i = 1, 2, \ldots, n_r$, we number all the units in the increasing order of $b_{sp.0.i}$ so that the most economic unit is $j = 1$, and the least economic one $j = n_r$

$$j = 1, 2, \ldots, n_r$$

Consider the moment of completing the repair t_c which is close to the annual load maximum. Assume that all the units of the

power system are to be available by this moment. The equivalent differential characteristic of the pool is plotted for the complete availability, and the feasibility condition of outage of the last unit is checked. If the condition is not satisfied, i.e. if $c_s b_s < c_i b_{sp,i}$, any outage of the units will lead to overconsumption of fuel. If the unit outage is feasible, it is stopped for repair and a new differential characteristic of the system without the last unit is plotted. A new value of b_s is found from it and the feasibility of outage of the last but one unit is checked. Such a procedure is continued till the outage feasibility condition is satisfied or one of the constraints is violated.

Now find the moment of the latest beginning of repair for one of the stopped units, $t_2 = t_k - t_{r,\min}$. Plot a new differential characteristic for the unit with regard to the units under repair and again check the feasibility of outage of the least economic unit.

Thus we will arrive at the natural sequence of unit repairs. The larger units will be closer to the deepest point of the load curve valley, while the smaller ones at the beginning and end of the repair period. As a rule it is impossible to arrange all the units to be repaired according to the natural sequence. In this case the maintenance schedule is optimized by one of the discrete programming methods: dynamic programming, branches and boundaries or directed exhaustion.

9.9. Planning and Accounting of Repair Jobs in MCS

To plan repairs of the plant equipment and transmission lines, use is made of computers. The repair progress is also accounted for by computers. Such accounting allows a more complete estimation of the work volume performed. It improves book-keeping, working time allocation and major repair scheduling. Let us consider planning and accounting of repair jobs on networks.

Major repair chart. The main primary document is a specially prepared major repair chart (MRC) containing the following data:

— the address of the installation and the date of repair starting;

— the duration of outage, travel to the site, preparation for work;

— the repair costs including labour cost, equipment used (in machine-hours) in types indicated by the respective codes, the volume of work performed (the operation types are also coded);

— the numbers of the supports to be replaced (code of the equipment to be replaced).

Peculiarities of MRC processing on computer. The major repair information is prompt. It may be transmitted to RPD CC by teleprinter or post. Punching, input and creation of the major repair data file are accomplished in a regular manner. However, processing

is somewhat peculiar. The peculiarities reside in that the contents of the wage rate book are additionally inserted into the machine memory. The book contains the description and code of the operation, labour cost per work unit, rated labour input and wages per work unit. This makes it possible to compare the actual (reported) and planned indices of repair. The book can be used for preparing and printing the repair estimate.

The secondary documents. Depending on the request, the secondary documents may cover the place of repair (installation), the volume of the work performed, the amount of consumed material of a given type, and also data on the equipment and manpower employed.

Preparing maintenance schedules. The source document is the damage statement compiled on the basis of the inspection and operation analysis of the equipment. The statement lists the codes and volumes of the operations to be performed.

The work cost and the required manpower, materials and equipment are calculated for some operations. For convenience, all jobs are divided into preparatory (transportation of supports, preliminary assembly, etc.) and repair jobs. When calculating the required manpower, the time of transporting the workers to the installations should be taken into account.

The schedules are prepared for different equipment in compliance with the established maintenance intervals. The necessary materials, manpower, mechanisms and transport are determined. The estimates, orders, statements on work performed are prepared. The repair accounting task is usually linked with the equipment inventory as regards the data used. The equipment inventories are updated according to the scheduled and unscheduled repairs.

Preparing repair estimates. The major repair costs are found by multiplying the work volume set forth in the schedule by the unit costs for each item, summing up the work types for each installation and a group of installations. The expenses are itemized into wages, transportation costs, material costs. The output documents are the major repair estimate, labour input and cost summary, bills of materials and material requisition, legend for the major repair schedule.

Calculating maintenance schedules. The problem comprises elaborating the network repair schedules, checking of the work performed, changes in the schedules according to the limitations in material and manpower resources.

9.10. Record Keeping of Main Electrical Equipment and Control Means

The task of record keeping of the main electrical equipment and control means involves creation of the information models or banks with a great number of elements for each type of information. The

banks are prepared on the basis of the certificate data and test results and represent the source information for many control problems. Let us consider the procedure of collecting information on the condition of the electric network, i.e. the construction of the information model of the network.

The information model is constructed as follows. The data on each network segment interconnecting two nodes are gathered and entered into a special form. This form is the source document. After verification and approval the form is transferred to RPD CC. The document is transferred to the machine medium (punched card or tape). After the input the computer executes the initial data vetting and creates a file on a magnetic tape or disc. The file is printed out for verification. If errors are detected a correction file is prepared and forwarded to RPD. The corrections are transferred to the medium and set into the computer. The list editing ends in introducing the corrections.

Notice that the data are prepared in such a way only once when committing the system. Further the file is merely updated in the course of operation of the network.

Updating. The files are updated as follows. Inserted successively into the computer are the old file which is to be updated and a new or correction file. The erroneous data are deleted from the old file and replaced with new information from the correction file. In other words, two files merge into one new (updated) file. To search the required information, the file should be sorted according to a given flag (or flags).

Software. The software necessary to construct the information model should comprise five programs:

— declaration which processes one form;
— file-organization routine which creates a file of a given type;
— updating routine which updates the files;
— report routine which organizes output of reports on request in the desired form;
— sort/merge routine (utility).

Network condition form. Consider the creation of the network condition file in more detail. The main document is the network element condition form. It comprises a number of attributes (labels). These can be divided into several groups characterizing:

— address (the number of the utility, region, nodal substation, line, segment, the name of step-down substation, sectionalizing switch (breaker), the numbers of the initial and terminal supports);
— transmission line parameters (year of commissioning and of the last repair, voltage, number of phases, wire grade and gauge, number of insulators (glass or porcelain), segment length, characteristics of transformers: power, number, year and type of installation, manufacturer, type and number of switches (breakers);

— transmission line route (length of segments using supports of different types, swath width, year of recent cutting, data on protective cables (cable grade and gauge, support number), number of crossings with other transmission lines, railway tracks, communication lines, etc.).

Report documents. Various types of report documents can be made on the user's request. These can be classified into check documents used for verification and updating, summaries for the line, nodal substation, ENF or RPD, grouping documents which divide the equipment according to a certain feature (for instance, type or power of the transformers, type of supports or gauge of wires, etc.); documents which characterize the development of the networks; statistical reports in forms approved by the Central Statistical Department.

Advantages. The exhaustiveness and validity of the available data are improved, which provides for a more grounded scheduling or routine and major repairs. This system can supersede equipment certificates. Notice that the source information can be utilized for other MCS tasks, e.g. reliability analysis. Using the major repair data, it is possible to automate the correction of the source information.

Accounting of equipment condition. This problem covers transmission lines, substations, distributing networks, protective gear, telecontrol and communication facilities. It involves record keeping of equipment troubles and estimation of the need for repairing particular units.

10

SHORT-TERM OPTIMIZATION OF POWER SYSTEM

10.1. Load Distribution in Interconnected Power Systems

Hierarchy of load distribution in daily planning. Load distribution in USSR PG is performed according to the existing hierarchy of the routine control and may include four levels: the power grid of the USSR (USSR PG CCD), interconnected power system (ACB), regional power system (RPS), and power plant (PP).

Load distribution begins from the top level. PG CCD prepares the power balances for the pools and schedules main interchange power flows (IPF) which balance the operation of PG. The optimal load schedules for each pool (interconnected system) are determined. The calculations widely utilize the equivalence technique with replacing the interconnected power systems or groups of plants by one equivalent characteristic from the energy characteristic library. An example equivalent scheme of the USSR PG is shown in Fig. 10.1.

The load and the interchange power flow schedules are reported to each pool and the second optimization stage is carried out, i.e. optimal distribution of load between the power systems of the pool in compliance with the assigned interchange power flow schedule. At the second stage the electric network characteristics are accounted for in detail (for instance the equivalent scheme of North-Western IPS shown in Fig. 10.1 as one node comprises up to 60 nodes). The load schedules are detailed and optimized for each large station as well as for the rest part of the power systems.

Sometimes the optimization procedure ends here, though not all the potentialities of it have been used up. The power systems equipped with their own computers usually perform additional optimization of load distribution between the stations of the system according to the general load schedule assigned by ACB. Besides, in large plants the intra-station operation is also optimized.

Note that as the optimization problem descends from the top level downwards, it becomes more and more complicated. The equivalent characteristic for large pools is usually smooth and allows the use of the convex programming methods. As the size of the object decreases, the discontinuities of its equivalent characteristic become more and more prominent. Thus, at the USSR PG and ACB levels the optimal daily availability can be neglected, whereas at the power system and especially at the intra-station levels such an optimization is mandatory.

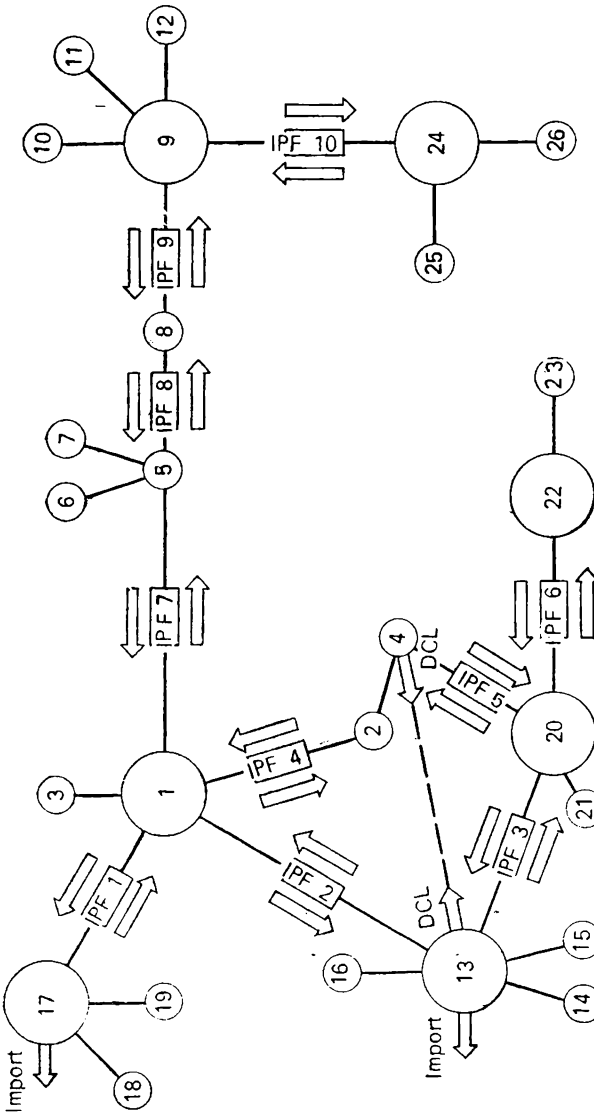


Fig. 10.1. Daily scheduling diagram of USSR PG

1—central IPS; *2*—hydro plant named after XXIIth congress of CPSU; *3*—equivalent HP; *4*—Volgograd power system; *5*—Kuibyshev area of Middle Volga IPS; *6*—hydro plant named after Lenin; *7*—Saratov Hydro; *8*—Bugulma area of Middle Volga IPS; *9*—Urals IPS; *10*—Kama Hydro; *11*—Votkinsk Hydro; *12*—other Urals hydro plants; *13*—South IPS; *14*—Kremenchug Hydro; *15*—Dnieper Hydro (Dneproges); *16*—other HPs of South; *17*—North-West IPS; *18*—Pyavinsk Hydro; *19*—other HPs of North-West; *20*—Northern Caucasus IPS; *21*—Northern Caucasus HPs; *22*—Trans-Caucasian IPS; *23*—Trans-Caucasian HPs; *24*—IPS of Northern Kazakhstan; *25*—Bukhtarminsk Hydro; *26*—Ust-Kamenogorsk Hydro; IPF—interchange power flows

At present, load distribution at the PG CCD, ACB and usually at the power system levels is based on substantially identical programs utilizing the convex programming methods.

Programs prepared by All-Union Research Institute of Power Industry and the Computer Center of the Main Engineering Department. These programs are often used to optimize the daily operation of the interconnected power systems. These programs are marked by the Russian letters А, Б and В. The figures following the program index correspond to its modification and (or) year of its development, e.g. program В-3/75.

Programs А are designed to plot the incremental rate characteristics of units and plants. There are several variants of such programs, among which two main modifications: АТ intended to plot the PHP characteristics and АК for plotting CPP characteristics, and programs АИ. Program АК/75 allows calculation of equivalent characteristics (consumption and incremental rate characteristics) with a simultaneous distribution of load between the station units (boilers, turbines). Another modification of this program provides for calculating the dependence of the auxiliary power consumption and net specific consumption of fuel upon the load.

Program АК/77 is intended to plot a characteristic of a boiler. It utilizes the differentiation of the loss characteristics (or boiler efficiency). The boiler loss-versus-steam generating capacity curve is initially approximated by a suitable polynomial of a low degree.

Program АТ/75 calculates the optimal operation and equivalent characteristics of PHP irrespective of its thermal scheme configuration and optimizes both the heat and power load distribution. To cover thermal loads, reducing and cooling devices, peak hot-water heaters, and peak hot-water boilers are used. A controlled extraction turbine is a combination of two turbines connected in series—back-pressure turbine of high or medium pressure and a condensation turbine of low pressure.

The source data for both programs are incremental rate characteristics of the boilers, consumption characteristics of turbines sections, data on unit interconnection, total values of thermal loads of each header. The programs utilize the gradient method. The constraints are accounted for by the penalty functions. The TPP optimal operating conditions, total electric power and total fuel consumption are determined for each system incremental rate.

The set of programs АИ sets up on magnetic media a library of unit and plant characteristics for a given thermal scheme. The results of calculations performed by programs АТ and АК are received by set АИ and are written in the library.

Programs Б perform calculations and optimization of normal operating conditions of a network. Program Б-2/75 performs only calculations of the network without optimizing its operation, prog-

ram Б-4/75 refines optimal distribution of active and reactive powers of installations, determines optimal voltages of the regulated nodes and transformation ratio of variable-ratio transformers. Since this program requires considerable time for execution, it is often replaced with program Б-2/75 performing partial optimization without changing the active powers of the consumers.

A new modification designated Б-2/78 combines to a sufficient extent the potentialities of programs Б-4/75 and Б-2/75. It may be used both for a complex optimization with respect to active and reactive powers and for optimization of the network only. This program may also be used to correct the operating conditions.

Program Б-3/75 is intended to calculate partial derivatives of active power network losses.

Programs B are used to optimize operation of the power systems and pools. The programs are applicable both for a period of several days and for a period equal to or less than 24 h. At $t < 24$ h, program B allows prompt correction of operating conditions. Modification В-2д/77 can be used for such a correction in the man-machine dialog mode. It ensures prompt correction after 10-15 min with regard to inserted nodal load telemetry data and automatic forecast of the general load schedule of the systems.

10.2. Coordination of Subsystem Operation

If load distribution is performed in a hierarchic power system, the subsystem operation is to be coordinated. The coordination can be done in two ways: by assigning the intersystem power transfers (power transfer coordination) and by changing fictitious cost of the energy resource in each subsystem without assigning power transfers (energy resource cost coordination).

The power transfer coordination. Assume a fictitious power pool to comprise only two power systems, S1 and S2. After load distribution is performed at the level of the power grid the intersystem power flow (ISPF), balancing operation of the pools, is assigned. Using the equivalent characteristics of the power systems at the ACB level, optimize load distribution between the power systems and determine the load schedules for each of them. With the given general load and intersystem power flow schedules, each power system carries out load distribution between its power plants. In this case the equivalent characteristics of individual plants, rather than of the entire power system, are used. At this stage, the electric network is analyzed in far greater detail with including both the high- and medium-voltage nodes. The optimization of the load distribution in the power system is followed by optimizing the load of each plant (group of plants).

Assume that by the end of the optimization process we obtain the equivalent characteristics of both power systems. If they match

the equivalent characteristics used at ACB, the optimization procedure may be regarded completed. However, the equivalent characteristics usually change owing to some differences in the availability and network scheme. If this is the case, return back to the ACB level, redistribute the load between the power systems, replot the equivalent characteristics, and so on.

Energy resource cost coordination. Another method of coordination is to allow each power system to determine the intersystem power flow independently, i.e. to include it into the system-controlled variables. The ACB dispatcher distributes the load between the power systems by their equivalent characteristics and informs the power systems only of the general load schedules without assigning the intersystem power flows but includes the latter in the load schedule of the power systems. Each power system, distributing the assigned load schedule, optimizes the load of each plant. Simultaneously a certain value of the power flow is calculated. The power flow from the first system will not be equal to the power flow from the second system because of differences in the equivalent characteristics. In this case the ACB dispatcher should change the fictitious cost of the energy resource (Lagrange multiplier) for each system and redistribute the load between them, and so on.

Notice that changing the fictitious cost of the energy resource, the ACB dispatcher deteriorates the performance of the pool on the whole, since optimal operation is possible only if the fictitious costs of the first and second systems are equal. This means that the required power flows can be provided only at the expense of the local objective functions. Consider the trade-off procedure and then discuss the first and second coordination methods at greater length.

10.3. Methods of Control in Hierarchic System

The hierarchic system control is considerably complicated because the superior level has no complete information on the condition of the plants of the subordinate level. The lack of exhaustive information, which is the essence of the hierarchic system, necessitates the use of iteration control methods to cope with the cases when the subsystem criteria do not match those of the entire pool. It is also possible that the operators at the lower level will try to conceal some production resources from the superior bodies. The hierarchic system control is confined to partitioning the entire system into separate elements or subsystems. Such a partitioning is called decomposition. The optimal functioning conditions are selected in these subsystems and then the conditions of couplings interconnecting the subsystems are coordinated. This involves some compromise deteriorating the conditions of separate subsystems.

Organization of trade-offs. Let a lower level comprise s subsystems.

The condition of each of them at the present moment of time is described by the state vectors of the equal dimension $\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_s$ (if necessary the vector dimensions are equalized by adding zero components). The entire system is described by the general state vector $\mathbf{X} = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n\}$. Let $E_1, E_2, \ldots, E_s$ be the objective functions (criteria) of each subsystem. They are continuous and concave. It is necessary to optimize the behaviour of the entire system, so that

$$\sum_{i=1}^{s} (E_{i,0} - E_i) \Rightarrow \min \tag{10.1}$$

where $E_{i,0}$ is the local extremum of the ith subsystem with the provision that the latter is isolated from all other systems.

Assign to F_i such a bounded, closed and convex subset, that if $x_i \in F$, then $| E_{i,0} - E_i | \leqslant \varepsilon$, i.e. the losses of the local subsystem objective function are within the admissible limits. If Φ which is the intersection of all subspaces, is not a null set, i.e.

$$\Phi = \bigcap_{i=1}^{s} F_i \neq \varnothing \tag{10.2}$$

then with the tolerable losses all the systems are coupled (vector $\mathbf{X}$ has the coordinates common for all the subsystems), and the problem is solved. If $\Phi = 0$, trade-offs for the local objective functions

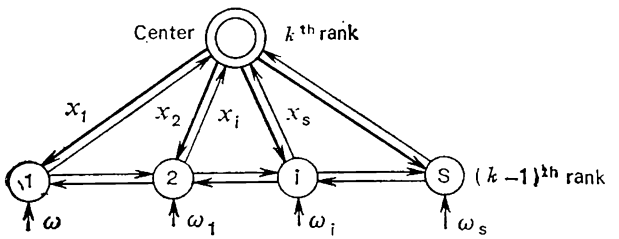


Fig. 10.2. To interaction of control levels in two-level hierarchic system

are needed. The optimization process is temporal. The trade-off function $g(t)$ is introduced. The maximum value of the local subsystem criterion decreases with time and each subspace F will monotonically expand. At a certain moment t, set Φ will not be empty. With the adopted E_0 and F constraints, the set will comprise at least one point. The solution with such an approach depends on the procedure of using $g(t)$ and on the value of penalties (trade-off functions) imposed on the subsystems. The complexity of choosing a single criterion becomes the problem of choosing function $g(t)$ and the sequence of its application to the subsystems. The trade-off process is usually iterative.

Let us focus our attention on the organization of level interaction in control of a large system. The example will be a two-level control system (Fig. 10.2) wherein the ith level is the control center and

the lower $(i-1)$th level is the subsystem. We mentioned above that two control methods are possible. Consider both of them.

Method of assigning dispatch schedule or method of decomposition with intermediate power transfers. This method presupposes that the center controls only the system parameters γ, but does not interfere in regulation of other parameters of individual subsystems. The subsystems regulate them independently relying upon the criteria set forth by the center. Again $\mathbf{X}$ is the vector of the general system variables. Divide it into two components: a set of subvectors $\mathbf{M} = \{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_s\}$ of subsystem parameters $\mathbf{x}_i \in \mathbf{X}$ and γ, i.e. the parameters subject to direct control by the center

$$\mathbf{X} = \{\gamma, \mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_s\} \tag{10.3}$$

Vector γ is formed by excluding some control parameters $\gamma = \mathbf{x}_{1,\gamma}, \mathbf{x}_{2,\gamma}, \ldots, \mathbf{x}_{s,\gamma}$ from vector $\mathbf{x}_i$ and transferring them to the center. We denote by vector $\Omega = \{\omega_1, \omega_2, \ldots, \omega_s\}$ the external factors. The vector includes a random component $\omega_i = \omega_{f,i} - \omega_{\xi,i}$ where $\omega_{f,i}$ is the forecasted value, $\omega_{\xi,i}$ is the deviation from the forecast (forecast error).

The control interrelates the variables. For the ith subsystem, it can be written in the vector form (subsystem constraint)

$$\mathbf{W}_i(\gamma, \mathbf{x}_i, \omega_i) = 0; \quad \forall i \in s \tag{10.4}$$

The system control (constraint) is represented by

$$\mathbf{W}_0(\gamma, \mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_s) = 0 \tag{10.5}$$

The objective function is the minimum expenses in all the subsystems

$$E = \sum_{i=1}^{s} I(\mathbf{x}_i) \Rightarrow \min \tag{10.6}$$

where $I(\mathbf{x}_i)$ is in the general form a random function resulting from equipment characteristic spread, weather impact, etc.

Constraints. The variables can be restricted by the constraints, e.g. of the type

$$p_i(\mathbf{x}_{i,\min} \leqslant x_i \leqslant \mathbf{x}_{i,\max}) > p_{0,i} \tag{10.7}$$

where $p_{0,i}$ is the given probability of satisfying the constraints (for more detail, refer to Section 5.3).

The goal of the center is to find with the above constraints (10.4) and (10.5) that

$$\overline{\mathscr{E}}\left(\sum_{i=1}^{s} E_{0,i}(\gamma)\right) \Rightarrow \min \tag{10.8}$$

where $\overline{\mathscr{E}}$ is the mathematical expectation; the value of $E_{0,i}(\gamma)$ is found for each given γ from the minimization problem $\overline{\mathscr{E}} E_i(\mathbf{x}_i, \gamma)$

solved in each ith subsystem by the stochastic programming methods. In this case both the constraints are satisfied.

The solution is found by iteration as follows.

1. The center informs the subsystems of the predicted vector $\boldsymbol{\gamma}$.

2. The subsystems minimizing E_i with their constraints, find the optimal values of parameters $x_{0,i}$ (but do not implement them) and determine gradients $\mathbf{G}_i$ of function $\mathscr{E}(E_i)$ by the external parameters

$$\mathbf{G}_i = \frac{\partial \overline{\mathscr{E}}(E_i)}{\partial \boldsymbol{\gamma}} \tag{10.9}$$

Gradient $\mathbf{G}_i$ is the local characteristic of relation $E_{0,i}(\gamma)$. Each ith subsystem reports to the center those components of vector $\mathbf{x}_i$ which are incorporated in the general system constraints (10.5), and vector $\mathbf{G}_i$. It is assumed that the given vector $\boldsymbol{\gamma}$ satisfies all the system constraints, i.e. the systems inform the center of the need for updating $\boldsymbol{\gamma}$. If some inequalities become equations with a given $\boldsymbol{\gamma}$ (the constraint limit is reached), the subsystem reports an admissible, from its point of view, variation of $\boldsymbol{\gamma}$, i.e. indicates the set of vectors towards which variation of $\boldsymbol{\gamma}$ will violate the system constraints.

3. The center determines the permissible direction of l and, changing $\boldsymbol{\gamma}$, makes step h, introduces correction $\Delta\boldsymbol{\gamma} = lh$ and reports this to the systems.

4. The subsystems additionally optimize their operation in view of $\Delta\boldsymbol{\gamma}$ and determine whether step h is permissible from their stand. If necessary, they correct it to the permissible value h_p.

5. The center's next step is $h = \min\{h_{p,1}, h_{p,2}, \ldots, h_{p,s}\}$ and it introduces the respective correction into $\boldsymbol{\gamma}$. The process repeats, starting with Item 1 till $\Delta\boldsymbol{\gamma} \geqslant \varepsilon$ but may end earlier for lack of time. The obtained vector $\boldsymbol{\gamma}$ is supplied to the subsystems as a control directive. The decision making process is substantially simplified, if it is possible to approximate constraints A and B depending on $x_{0,i}(\boldsymbol{\gamma})$. As the information is accumulated, self-instruction is utilized and the approximation precision is improved. In the limit, if exhaustive information on said relations is available, the unique directive value can be immediately obtained.

Decomposition with intermediate costs. The control task is confined to the solution of the following minimization problem

$$\overline{\mathscr{E}}\left\{\sum_{i=1}^{s} I_i(x_i) + \lambda_0(\boldsymbol{\gamma}, \mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_s) + \sum_{i=1}^{n} \lambda_i W_i(\boldsymbol{\gamma}, \mathbf{x}_i)\right\} \Rightarrow \min \tag{10.10}$$

where $\lambda_0, \lambda_1, \lambda_2, \ldots, \lambda_s$ are the Lagrange multipliers (dual estimates or fictitious cost of fuel) of the system and subsystem constraints. If all the constraints are satisfied, the second and third

terms of the expression go to zero. If the first constraint can be represented as a separable function, i.e.

$$W_0(\gamma_0, \mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_s) = W_{0,o}(\gamma) + \sum_{i=1}^{s} W_{0,i}(\mathbf{x}_i) \quad (10.11)$$

then (10.10) can be written

$$\overline{\mathscr{E}}\{\lambda_0 W_{0,o}(\gamma) + \sum_{i=1}^{s} [I_i(\mathbf{x}_i) + \lambda_0 W_{0,o}(\gamma) + \lambda W_i(\gamma, \mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_s)]\} \Rightarrow \min \quad (10.12)$$

Denote the expression in parantheses by $\mathbf{L}_0$.

The solution is as follows.

1. The center informs the subsystems of values of γ and λ_0. The latter has the meaning close to certain costs because of violation of the constraints.

2. The subsystems find the minimum of the mathematical expectation of $\mathbf{L}_{0,i}$ with subsystem constraints (A) and inform the center of the value of $W_{0,i}$ and gradient $\mathbf{G} = \frac{\partial \mathbf{L}_{0,i}}{\partial \gamma}$, and the impermissible variation directions of vector γ, if any.

3. The center determines and reports to the subsystems vector $\mathbf{L}$ of the variation direction of vector γ calculated with due regard for gradient

$$\mathbf{G} = \sum_{i=1}^{s} \frac{\partial \mathbf{L}_{0,i}}{\partial \gamma} + \lambda \frac{\partial W_0}{\partial \gamma} \quad (10.13)$$

and reports the direction of λ_0 variation

$$\frac{\partial \lambda_0}{\partial h} = \sum_{i=1}^{s} W_{0,i}(\mathbf{x}_i, \gamma) + W_{0,o}(\gamma) \quad (10.14)$$

If the operational constraints are satisfied, the variation of the vector λ_0 component is null.

4. The subsystems report the value of permissible step h_p. The center determines the optimal step h_o and then assumes its permissible value $h_{p,o}$.

5. The vector corrections are reported

$$\Delta\gamma = h_{p,o}\mathbf{L} \quad \text{and} \quad \Delta\lambda_0 = \frac{\partial \lambda_0}{\partial h} h_{p,o}$$

The process is repeated from Item 2 till γ and λ_0 stop changing. The calculations can be accelerated by approximating relations $\lambda_0(W_0)$, $\frac{\partial \mathbf{L}_0}{\partial \gamma}(\gamma, \lambda_0)$.

The second method is better for higher levels of hierarchy which may have no effective variables. Its convergence is slower, which is tolerable for the high hierarchic levels.

The methods of two- or three-level control require organization of the intermachine exchange between CCs of different levels during iteration. With the existing tape-to-tape connection, even two or three exchange iterations (which are explicitly scarce) are rather challenging, since the routine planning in the pools should be carried out very quickly. Therefore, the multilevel iteration procedures are very seldom today in decision making. As the direct intermachine communication channels are implemented, such methods will have wider use in the control practice. At present, a single-level (usually ACB-level) optimization is performed on the basis of the equivalent characteristics of large generating nodes, and then the fixed values of the intersystem power flows are utilized for additional optimization of the generating unit (system, plant) by the given equivalent characteristic.

10.4. Real-Time Control of Hydro Unit Availability and Operation

One of the most vital goals of hydro plant management is the rational control of the unit availability. The availability strongly affects the economic indices of hydro plants. Non-optimal availability may decrease the hydro efficiency by 1-5%.

A system hydro plant performs various functions: it participates in active power balancing, regulates power within a wide range, controls frequency and voltage, contributes to emergency and repair reserves. The normal execution of these functions is based on a proper choice of the units and their active and reactive powers.

The uncertainty of the source information impedes the optimization of the availability. Power system loads, frequency, voltage, available powers of the stations and usable water resources and other factors are random variables. The HP performance is also somewhat uncertain.

Thus, the choice of the HP units is a crucial part of the system problems and it should recognize all the relations with other operational problems of the system. This can be achieved by using the principle of hierarchy and decomposition of the system control problems. The hierarchic approach allows for creating a priority scheme for solving separate problems, simplifying the formulation and computational algorithms, and decreasing the solution time. HP APCSs are being developed today so that all the later discussion proceeds from the assumption that the intra-station optimization is carried out not only in routine planning but also in the real-time process. The methods and algorithms of intra-station optimization are given in Chapter 8. This part of the book deals only with the contents of the real-time control problems.

1. Regulation of active powers of the operating units to maintain the rated frequency of the system.

2. Regulation of reactive powers of the units to maintain the rated voltage at the check nodes.

3. Cutting in the units to provide a frequency standby (frequency f is controlled).

4. Cutting in the units to provide an emergency standby (spinning reserve is controlled).

5. Fast starting of the units (in mode GEN or SC) to maintain the rated voltage; voltage and voltage temporal variation rate $a = \frac{dV}{dt}$ are controlled. If $a > a_p$, the active power spinning reserve should be increased as fast as possible.

6. Cutting in the units for operation in mode GEN or SC for maintaining the permissible voltage

$$V_{\min} \leqslant V \leqslant V_{\max}$$

7. Optimization of availability and active powers of the units for the present values of resistive load.

8. Optimization of availability and active powers of the units for the present values of reactive load.

9. Correction of plant powers and choice of availability and active powers of the units for maintaining the rated values of discharge rates or tail water elevation.

10. Routine planning of availability and operation of the units, e.g. day in advance.

All the above problems are optimization ones. Four algorithms will be enough to solve all of them: optimal distribution of resistive load between the units (for problem 1), optimal distribution of reactive load between the units (for problem 2), choice of the unit availability according to the available power (for problems 3-5), optimal availability and operation of the units (for problems 6-10). The problems are interconnected by feedforwards and feedbacks, thus forming a single intra-station optimization set.

The above-listed ten problems ensure a temporal hierarchy of the intra-station optimization procedure. The first stage includes elaboration of short-term plans on the basis of the forecast source data (problem 10). The short-term plan covers from 24 h to several days. At the second stage, the plan is updated on the real-time basis according to the current operational parameters (problems 1-9). The need for updating arises when the forecast differs from the actual operating conditions.

The two-stage scheme is usually employed to control the active power balances of the power system and stations. The load schedules for separate plants are determined by the system active power forecasts. To cover the assigned load curves, the availability of the units is optimized and the plant resistive load is distributed between

them in the optimal way. Next the planned availability and performance of the units are subject to real-time updating.

The reactive power balances are controlled, as a rule, only on the real-time basis by the current values of the controlled variables. The difficulties of planning the system reactive loads (they are planned only in certain cases) usually make the planner omit the short-term planning stage. When the ENERGIYA MCS is implemented scheduling reactive loads is expected to have wider use. The reactive power balances should not violate those of active powers.

The problem solving methods are given below.

Problem 10 involves planning the availability and reactive powers of the units. Its solution with regard to reactive powers is possible only when the predicted reactive power schedule of the plants $P_Q(t)$, generating unit availability and resistive loads are known. The units operating in the GEN mode participate in the plant reactive load balance and their reactive power depends on the active one. If the available reactive power of all the generators is insufficient, additional units can be engaged in the GEN or SC mode. The task is to find the rational availability of the units for minimizing the discharge losses, i.e.

$$\Delta W = \sum_{t=1}^{t=m} \Delta Q_t \Delta\tau_t + \sum_{t=1}^{t=m} \Delta Q_{SC,t}\, \Delta\tau_t + \sum_{t=1}^{t=m} Q_{s,SC,t}\, \Delta\tau_{s,SC,t} \Rightarrow \min \tag{10.15}$$

where ΔQ_t are the plant discharge losses if the number of units in the GEN mode is increased over the optimal plan (the losses can be found if the number of units is increased over the optimal one); $\Delta Q_{SC,t}$ are the discharge (or active power) losses when the units operate in the SC mode; $Q_{s,SC,t}$ are the starting discharge when engaging SC.

The problem includes the following constraints:

(1) the vector of availability of SC in interval t is found from the number of units not included in the vector of availability of GEN;

(2) the plant reactive power balance is checked;

(3) the operating units are checked for reactive power reserve;

(4) the unit reactive power constraint is checked (the unit reactive power should be within permissible limits).

The solution of the problem takes into account the possibility of automatic change-over of the generators to the SC mode and vice versa. These operations ensure the interrelation between the control functions of the units participating in the active and reactive power balances. Besides, the change-over operations decrease the number of the start/stop cycles and cut starting costs.

Problem 1. With the known availability of units the load is optimally distributed between them. The optimization criterion is the minimum discharge through the operating units.

Problem 2. This problem can be solved either independently or jointly with problem 3. Control of voltage (reactive power) presents necessary information on the reactive power of the plant and allows their distribution among the units. The uniform distribution of reactive power is most common.

Problem 3. If HP controls frequency in the system, it should have a definite spinning reserve. Reducing the spinning reserve is prohibited, since it may lead to emergency situation. Therefore, if the spinning reserve decreases, it should be restored as fast as possible by engaging any cold reserve unit.

Problems 4 and 6 are solved in a similar way.

Problem 5. Voltage regulation is reliable if the available reactive power of the operating units can be rapidly increased whenever necessary. The solution algorithm is based on the same premises as in problem 3.

Problem 7. If the HP actual operating conditions differ from those set forth by the short-term plan it becomes necessary to update the state variables, i.e. unit loads and availabilities.

Given: current load of the plant P_t, availability $K_{HP,0}$, unit characteristics, constraints. The optimality criterion is the discharge rate during the optimization period, but the strategy depends on the history. Now a new optimal availability of units $K_{HP,t} \in K_{HP,0}$, if load $P_t < P_{p,t}$, where $P_{p,t}$ is the planned load for period t. If $P_t > P_{p,t}$, the cold reserve units can be connected to operating units $K_{HP,t}$, i.e. $K_{HP,0} \in K_{HP,t}$.

The real-time updating dictates that the efficiency of control depends on the speed of response, which requires the use of fast programs for solving such problems.

Problem 8. This problem can be solved either independently or jointly with problem 7. Control of voltages (reactive powers) gives necessary information on the required reactive powers and permits determining the required number of SCs. The solution is similar to that used with problem 7. However, if the number of units operating in the SC mode increases, preference is given to those capable of changing over from the GEN to SC mode. When the number of units operating in the SC mode decreases, preference is given to those capable of changing over from the SC to GEN mode. The optimality criterion is (10.15). Problems 1-10 make up the availability efficient control subsystem (AECS).

Structurally AECS comprises four independent segments: source data preparation, efficient control program preparation (problems 1-10 are solved here), control efficiency analysis, production of control actions.

Let us consider the structure of each segment.

Source data and source data processing. Table 10.1 represents the

Table 10.1

Source Data for HP Intra-Station Optimization

Data	Purpose	Dimension in digits
Unit energy characteristics	Normative-reference	400/50
Other characteristics (to determine HP heads, unit reactive powers, etc.)	Same	60
Constants, weight indices, protective device operation estimates, etc.	Same	60
Schedules of active, reactive and reserve powers	Planning	150
Data on planned state of units, electric connections, cut-in transmission lines	Same	20
Constraints on power, availability and number of units	Same	10
Data on present state of units	Processing	10
Present values of operational variables of units, HPs, TLs, separate segments of plant	Same	50
Control signals and their execution monitoring	Same	50
Average efficiency, discharge, power, etc. of units, HP, HP segments	Report	100

contents of the main source data and their approximate characteristic obtained for an example of the Krasnoyarsk Hydro. The dimension of the normative-reference information is about 500 digits. Its main part is determined by the need of memorizing the individual energy characteristics of units. The numerator corresponds to the tabular representation of the characteristics in the computer memory, the denominator to the polynomial representation. The consumption (discharge) characteristics of the units are approximated to a sufficient accuracy by polynomials of the second or third degree.

The calculations reveal, that for the Krasnoyarsk Hydro the intra-station optimization can be performed with assigning the characteristics for the maximum and minimum heads during 24 hours, i.e. two energy characteristics are used for each unit. The hardware allows the tabular forms of the characteristics to be used.

The normative-reference information of Table 10.1 is used primarily for AECS. The planning and process information is more common and is utilized by other subsystems of HP APCS and for the dispatch control of the station. Some data are fed from the

superior control levels, others are collected from the analog and digital sensors arranged at the plant. The report information is also general and is employed for analyzing HP operation.

The above description shows that AECS should have special algorithms for preparing normative-reference information.

The most general problem of preparing the source data is the refinement of energy characteristics of the units. The hydro unit energy characteristics are found by full-scale testing. Since the programs of the full-scale tests are very complex, they can be performed comparatively seldom at intervals of 2 to 5 years or even more. The measuring equipment and test procedures ensure the efficiency measurement accuracy of up to 0.5-1%. The measured characteristics should be refined because the test conditions can differ considerably from the actual conditions of operation and the units are subject to aging. The calculations performed for the Krasnoyarsk and Novosibirsk Hydros show that each refinement changes the discharge rates of the units by about $\pm 1\%$. Such corrections are material for optimal operation of HPs.

The characteristics are updated according to the statistical and forecast data on various indices of HP operation, which necessitates the use of special statistical analysis and forecast programs. As a rule, such programs are not included in the HP APCS software, unless a special computer is provided. Therefore, the characteristic updating problems are not included in the first-priority tasks of HP APCS and make up the background.

After the creation of ENERGIYA MCS is completed, the statistical problems will be solved on a collective-use machine with real-time data transmission via the communication channels.

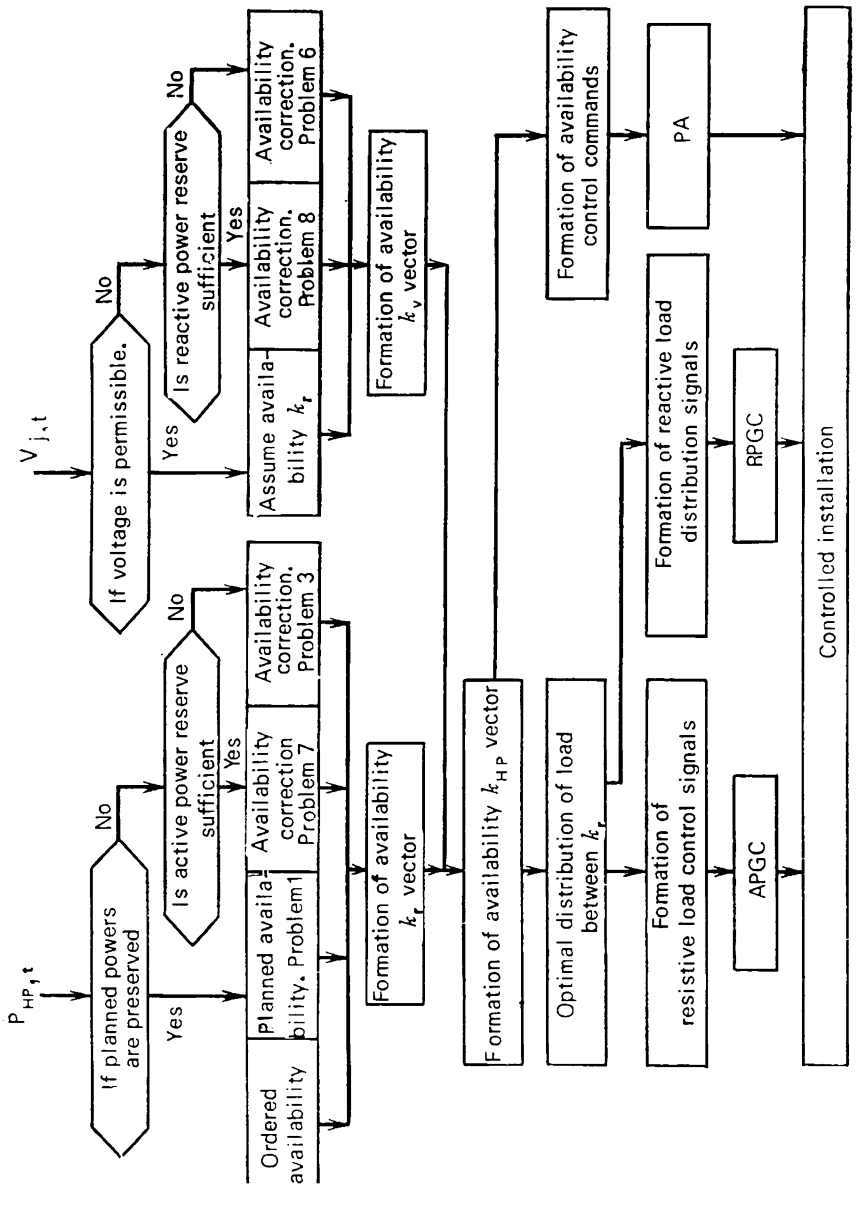
Efficient control program. The program solves problems 1-10. Fig. 10.3 shows the algorithm flow chart for the most typical case when the unit participation in the reactive power balancing is not scheduled, i.e. problem 10 is solved partially.

By checking the current active powers, one may come to a conclusion that the plan obtained at the short-term planning stage needs updating. If planned $P_{p.t}$ and current P_t loads match, the planned availability is preserved. In case of a mismatch, the reserve updating problem (problem 3) is solved first and then the planned availability (problem 7) is refined.

It is convenient to prepare the program on the modular principle, using separate modules of availabilities and load distribution.

Voltage monitoring executed in a similar manner makes it possible to find out if any additional units are to be connected for balancing the reactive powers and to determine the availability K_v.

The total availability is dictated by a combination of K_p and K_v and only then the load optimal distribution can be accomplished (problems 1,2).


$P_{HP,t}$
$V_{j,t}$
If planned powers are preserved
No
Yes
If voltage is permissible.
No
Yes
Is active power reserve sufficient
No
Yes
Is reactive power reserve sufficient
No
Yes
Ordered availability
Planned availability. Problem 1
Availability correction Problem 7
Availability correction. Problem 3
Assume availability k_r
Availability correction. Problem 8
Availability correction. Problem 6
Formation of availability k_r vector
Formation of availability k_v vector
Formation of availability k_{HP} vector
Optimal distribution of load between k_r
Formation of resistive load control signals
Formation of reactive load distribution signals
Formation of availability control commands
APGC
RPGC
PA
Controlled installation

As a result, the availability control commands are generated: cut in GEN, cut out GEN, cut in SC, cut out SC, change over GEN to SC, change over SC to GEN. The commands are instrumented by process automatics PA. Also generated are the operation control commands: adjust active power P_i and reactive power $S_{Q,i}$ on the ith unit. The commands are implemented via individual or group active (APGC) and reactive (RPGC) power automatics.

Table 10.2 represents some averaged estimates of algorithms for

Table 10.2

Realization of Intra-Station Tasks by Computer

No.	Description of task	Memory capacity (decimal system)	Computation time, s	Number of solutions per day
1	Planning availability and performance of units	800	60	1
2	Controlling units if Item 1 solution is valid	300	0.2	—
	Updating availability by active power balance	800	0.5	50
4	Updating active power reserve	250	0.1	2-5
5	Optimally distributing resistive load among units	550	1.5	100
6	Determining SC availability on real-time basis if Item 1 solution is valid	250	0.2	50
7	Determining availability of units in SC mode on real-time basis if Item 2 solution is valid and updating reactive power reserve	200	0.02	50

solving the above problems as applied to APCS of the Krasnoyarsk Hydro. The solution interval indicated in Table 10.2 was determined as follows. The operating conditions were updated at a rate of up to 4 times per hour. The algorithms of problems 5 and 6 run simultaneously and the total number of solutions is up to 50 times a day.

10.5. Estimation of Water Discharge for Spinning Reserve and Frequency Control

Spinning reserve is an important factor in improving the reliability of electricity supply. However, the use of the spinning reserve changes the optimal availability and causes additional consumption of water. The today's estimates of such a consumption are fairly

rough and a few works deal with the problem. We present hereinbelow the results of special studies which permitted obtaining certain quantitative characteristics.

Formulation of the problem. A special mathematical model was constructed to account for additional discharge. The problem is formulated as follows: find the minimum total daily discharge when the HP power balance is observed and the constraints on the permissible load of each unit are satisfied. Besides, the assigned power reserve constraint should be fulfilled i.e.

$$\sum_{i=1}^{n} P_{i,\,\max} \geqslant k_r P \tag{10.16}$$

where $P_{i,\,\max}$ is the maximum permissible power of the ith unit; P is the station load; $k_r \geqslant 1$ is the assigned reserve coefficient.

This is a typical problem of allocation. The need of recognizing the power reserve imposes an additional constraint but does not alter the essence of the problem.

To find the additional water discharge for spinning reserve, the optimization problem was first solved without accounting for constraints, and daily discharge W_o through HP turbines was determined. Then the same problem was solved in view of constraint (10.16) and daily discharge W_r was calculated again. The water discharge for the spinning reserve was calculated from the formula

$$\Delta W = \frac{W_r - W_o}{W_o} \tag{10.17}$$

To find the optimal allocation with neglecting the reserve, use was made of the equivalent characteristics obtained by the dynamic programming algorithm.

Optimizing allocation in view of spinning reserve. If the selected unit availability did not meet the reserve requirements, it was corrected. A new allocation was performed for a larger available power on the assumption that this would be one of the closest availabilities as regards the equivalent characteristic. The philosophy of choice is shown in Fig. 10.4. The equivalent characteristic of the station (dashed line) illustrates the minimum possible water discharge versus station power. Points a, b, c, etc. indicate the moments of changes in the availabilities. Let with load P, HP discharge Q and availability α the condition (10.16) be not satisfied. Then the nearest availabilities α_2 or α_3 which meet this requirement will be optimal. The supposition relies on the assumption that discharges Q and Q' of availabilities α_1 and α_2 differ slightly and the best availabilities α' (dashed line $a'b'$) are unlikely to appear between them.

The assumption is not too rigid, therefore a more detailed investigation was performed for allocation with recognizing the reserve.

The discharge characteristic updating method was used, which prohibited operation of the system with the chosen availability if it failed to satisfy the reserve conditions. In this case a new availability was found by a repeated run of the dynamic programming algorithm. The comparison revealed that the algorithms yielded substantially equal results though the method of exhaustion by

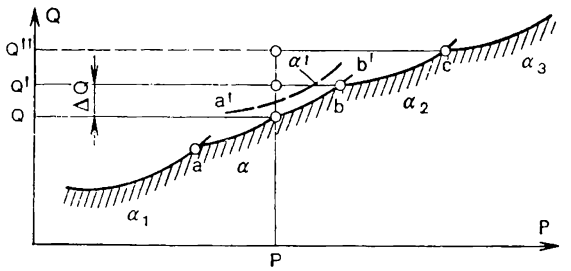


Fig. 10.4. Selection of availability in view of spinning reserve

the equivalent characteristic was far simpler. Therefore, this method was utilized for investigation.

The block diagram of the algorithm for allocation in view of reserve is shown in Fig. 10.5. The algorithm is solved as follows. During a direct run, the equivalent characteristic is plotted and the optimal availability (at $k_r = 1$, block *1*) is determined for load P_1. Using the assigned reserve coefficient k_r, find the required available power $R = k_r P$ (block *2*). Calculate the available power of operating units $P_a = \sum_{i=1}^{n} P_{i,\max}$. Compare values R and P_a to check that the reserve condition $P_a > R$ is met (block *3*). If *Yes*, turn to analysis of the second hour, if *No*, check if the reserve requirement can be met at all with the power available. To this end, calculate the total available power of the plant $P_{a,\max}$ and compare it with the reserve condition $P_{a,\max} > R$ (block *4*). If *No*, assume the total or the maximum possible availability $\alpha_{\max}$ (block *5*) and then change over to the next hour. If *Yes*, move step-by-step along the equivalent characteristic. To this end, increase power P for one discrete step and find the availability corresponding to such a load on the equivalent characteristic (block *6*). Check whether the availability remained unchanged (block *7*). If *Yes*, it does not satisfy the reserve requirements and one step $P + h$ more is added to the load value. If the availability has changed, check if the reserve requirement is met for the new availability and former load. The process ends as soon as the requirement is met.

When the reserves are high and the unit adjustment range is narrow, the planner moving along the equivalent characteristic

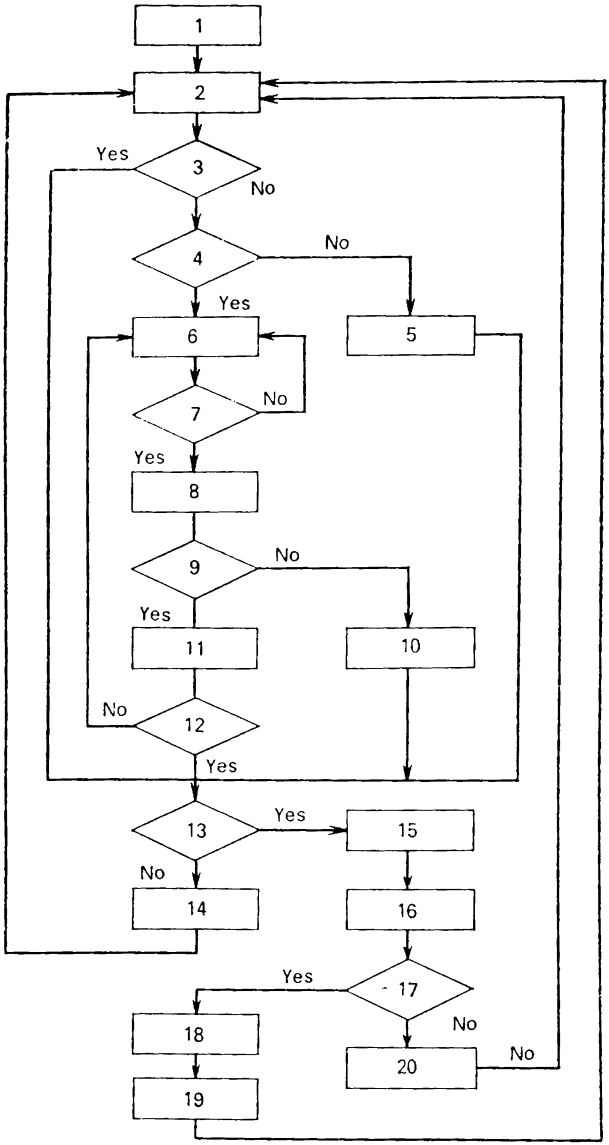


Fig. 10.5. Block diagram of algorithm for selecting availability in view of spinning reserve

can violate the constraint on minimum powers of units $\sum_i P_{i,\,\min}$ (block *8*). Therefore condition $P \geqslant \Sigma P_{i,\,\min}$ is additionally checked at each step (block *9*). If the condition is infringed without satisfying the reserve requirement, moving along the equivalent characteristic is ceased and the available reserve value is printed out (block *10*). Maximum power of units $\Sigma_i P_{i,\,\max}$ is also computed (block *11*) and the condition $R \leqslant \Sigma_i P_{i,\,\max}$ is checked (block *12*).

These calculations are performed for each hour of the day for which purpose the hour number is checked in block *13*. If not all the hours are scanned, change-over to the next hour occurs (block *14*).

During the reverse run, water discharge throughout the optimization period is determined (block *15*) and then additional discharge from reserve is calculated (block *16*). Then follow the checks: if all the values of k_r are scanned (block *17*). In block *18* the initial value of k_r is restored or change-over to the next value of k_r takes place (block *19*). In block *20* similar calculations begin for a new station load schedule.

The above method of estimating additional discharge of water presupposes that all the units perform the functions of a spinning reserve. After a slight modification the algorithm may account for the case when only some units execute the reserve functions. The developed method made it possible to analyze the factors affecting additional discharge for spinning reserve.

Let us consider a method of estimating additional discharge when HP participates in frequency control of the power system. In the course of control the HP load continuously fluctuates around its planned value. The fluctuations decrease the average efficiency of the station and cause excessive discharge of water. Special studies have been carried out for numerical estimation of the regulation (control) losses. A special algorithm and a program were prepared on the assumption that frequency control involves relatively low variations of power, which allows for neglecting the transient processes in the turbine and regarding the unit discharge characteristics as remaining constant throughout the control period.

The algorithm for taking into account water losses as a function of efficiency during frequency control is based on a combined availability algorithm. To estimate excessive discharge, the load probable variation area was chosen. It ranges from

$$P_{f,\,\min} = P\,(1 - k_f) \text{ to } P_{f,\,\max} = P\,(1 + k_f)$$

where k_f is the frequency control range coefficient which depends on the particular consumers and load variation distribution law.

For lack of other data, a uniform distribution was considered, though another distribution law is readily applicable. If the equivalent characteristic of the power system and the range of the most

probable load variation are known (Fig. 10.6), the average water discharge Q_a per hour can be determined as a ratio of the area of figure *abcd* to the load variation range. The algorithm envisages a successive variation of the hourly load P in both directions at a constant step h. Using the reverse run of the combined algorithm, the optimal distribution of the load among units is accomplished and the average discharge is calculated for each value of power $P' = P + kh$, where k is the number of steps. The daily total water discharge is found and compared with the value calculated without accounting for the efficiency variations. The difference determines the excessive discharge.

A sufficiently detailed block diagram of the algorithm for computing excessive discharge of water caused by efficiency variations is given in Fig. 10.7. The figures in the blocks indicate: *1*—a forward run and choice of optimal availability in view of the assigned reserve; *2*—a reverse run and calculation of daily discharge Q_d with neglecting efficiency variations; *3*—choice of load at the tth hour

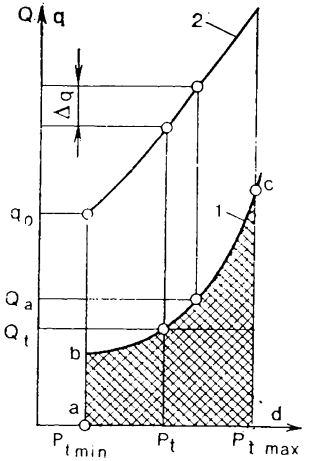


Fig. 10.6. Estimation of water excessive discharge rate at frequency control
1—discharge characteristic; *2*—differential characteristic

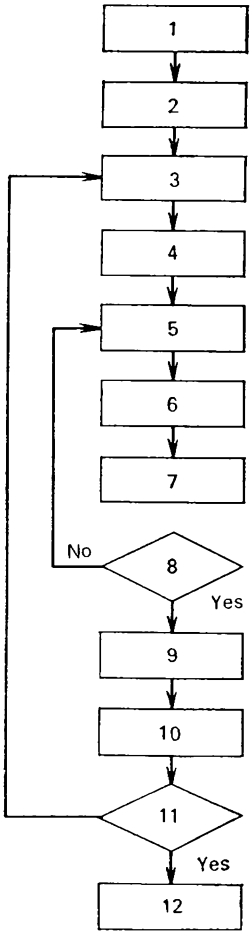


Fig. 10.7. Block diagram of algorithm for computing water excessive discharge rate at frequency control

P_t and finding its regulation range $P_{f,\,max}$, $P_{f,\,min}$; *4*—a reverse run for load $P_{f,\,min}$, calculation of increment q_o; *5*—step along power scale $P' = P + h$; *6*—calculation of all $P_{i,*}$; *7*—calculation of all $Q_{i,*}$; *8*—check of $P' > P_{f,\,max}$; *9*—calculation of the number of steps; *10*—determination of average hour water discharge Q_a;

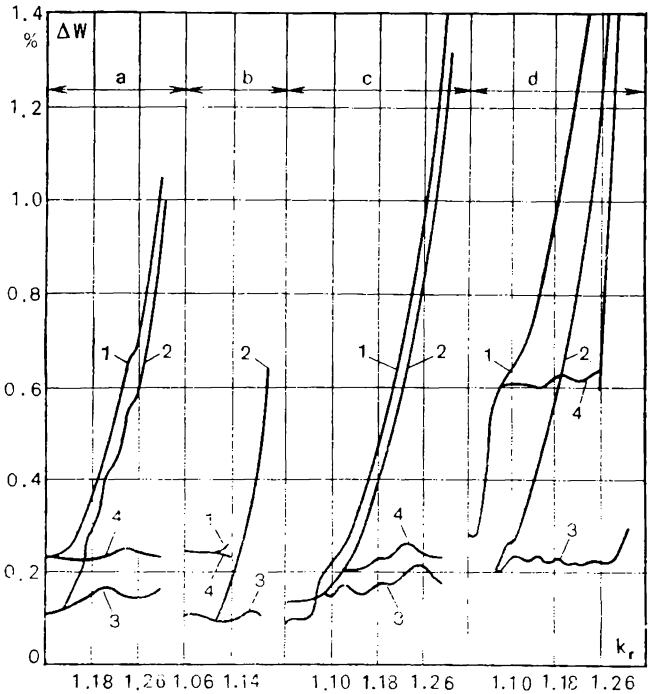


Fig. 10.8. Equivalent fuel excessive consumption versus reserve coefficient and load variation

(*a*) small system, normal adjustment range; (*b*) ditto, limited range; (*c*) large system, normal adjustment range; (*d*) ditto, limited range; *1*—full value of excessive consumption with wide range of load variation; *2*—ditto, with narrow range of load variation; *3*—fuel excessive consumption caused by frequency control, narrow range of load variation; *4*—ditto, with wide range of load variation

11—check if all the hours are scanned; *12*—determination of excessive discharge caused by efficiency variations.

Discuss some results of the studies. The calculations performed for a number of typical example plants revealed that the reserve and frequency control affects considerably the excessive discharge and should be taken into account when scheduling HP operation and estimating its technical and economic indices.

Figure 10.8 illustrates an example of variation in the excessive discharge (for hypothetical HP) as a function of frequency for different reserve coefficients k_r. It was assumed that the load basic fluctua-

tion zone lies in a relatively narrow interval. Two ranges were treated: from 0.96 to 1.04 P—normal, and from 0.92 to 1.08P—widened load fluctuation range. Two control ranges were considered: a normal and a shortened, which differed in the permissible value of power decrease $P_{i,\,\min}$.

Figure 10.8 shows that the losses caused by the efficiency variation are more profound with a low reserve coefficient. As the reserve coefficient and the total number of the operating units increase, the relative share of said losses diminishes whereas the spinning reserve losses grow higher. This stems from the fact that the equivalent characteristic is relatively flat in the zone of the large number of operating units and the efficiency variation is negligible. The control range of the unit has a particularly profound effect on the losses.

11

TECHNICO-ECONOMIC INDICES OF POWER PLANTS AND SYSTEMS

11.1. Planning in the Power Industry

Let us briefly consider the principal features of the system of planning used in the power industry of the USSR. The basic goal of the planning calculations is to correlate the electricity and heat demands of the national economy with the potentialities and resources of the energy utilities. Planning is carried out on two principles. The first principle "from demand to resources" has wider use and implies a complete satisfaction of the energy consumer's needs. The plans are corrected if the demand changes.

The second principle "from resources to demand" is utilized in deficit systems, with limited fuel resources of separate stations, for hydro plants with insufficient outflow regulation, at low capacity of transmission lines, etc. The plans are corrected if the resources change. Thus the planning is of iterative nature. The planning-correcting cycle may be repeated many times.

Balance method of planning. The balance method is the basic tool for coordinating the plans of production and consumption of various types of energy. The energy balances for the operational systems include: balances of separate types of energy (electricity, heat), power balances, balances of separate types and entire fuel, summary fuel-energy balances which are usually compiled with converting all the types of energy into equivalent fuel.

The balance problem is that of optimizing; it involves determining the outputs and performance of separate plants for minimum expenditures in the system. The balances are used for estimating technico-economic indices of the power system and plants and preparing the main planning documents.

Technical, industrial and financial plan comprises the state plan goals with respect to the types of the branch produce and measures to achieve them. The technical, industrial and financial plan is drawn up for a year and includes the following sections: basic indices of the production and economic activity of the plant, a production and realization plan, a production effectiveness improvement plan, planned technico-economic ratings and norms, a capital construction plan, a logistics plan, a labour and wages plan, an income, expenditures and profitableness plan, an incentive fund plan, and a finance plan.

The major role is played by the production and realization plan. It dictates to a large measure the plans of all other sections and comprises the directive goals and measures for utilizing system potentialities. To draw up the plan the entire complex of operational problems is to be solved: optimization of HP water reservoir regimes, optimal distribution of load in the system, choice of optimal availability and many many more. This book treats only the basic problems linked with the production and realization planning.

Planning stages. The technic and economic planning features a certain temporal hierarchy which is dictated by different terms of calculations. The first to deal with are the problems of developing the power utilities of the country and separate areas. Usually such problems are solved in three stages.

1. Long-term forecasting (20-25 years). At this stage, the planner determines the main requirements for the expansion of the power industry in view of the productive forces of the society, technological progress, utilization of new energy resources, etc.
2. Short-term forecasting (10-20 years). At this stage, the five-year plans are subject to feasibility study with respect to all indices.
3. Long-term planning (10-15 years).

In the power industry, these stages are devoted to forming the structure of generating powers, selecting the principal transmission schemes, basic parameters of stations, etc. The operational problems are of auxiliary nature and are solved by simplified algorithms. Thus, the calculations are performed with the average energy indices of the plants (efficiency, specific fuel consumption, etc.), average values of network power losses, and the like. Such a simplification is justified because the information required for solving the operational problems is either uncertain or probabilistic which precludes a sufficiently accurate solution. The subsequent stages refer to the operating systems and the weight and significance of the operational problems now drastically increase.

Two planning stages and one on-line control stage are allocated for the operating systems.

1. Short-term planning (1-5 years). At this stage, the technical and economic measures are planned. The optimization problems play an important role here and are solved many times. First, the request plan is drawn up and transferred to the superior bodies for refining the directive (check) indices of the plan. Then, while initially assigning the directive indices for the system, a draft plan is prepared which is also subject to change by the superior instances. The next stage is drawing up the main plan which now accounts for the approved directive indices.

The operating conditions are optimized on the basis of algorithms which widely utilize the equivalence technique for separate elements and characteristics of the system. The information is usually proba-

bilistic, but the algorithm is confined to the multilevel solution of a determinate problem.

2. Current planning for a day, week, month, quarter. The technological problems play the principal role at this stage. These problems are discussed at sufficient length in Chs. 6 through 9.

3. Real-time control of power production is effected with the use of the dispatch and automatic operation and process equipment.

Updating of the performance and technico-economic indices gains the utmost importance at the two latter stages. The official intervals of updating with refinement of the technico-economic indices are a month and a quarter. In fact the updating is performed continuously which is an indispensable condition of the required quality of supply, high reliability and economic operation of the system.

Planning problems. The basic technico-economic indices of the power utilities and system are determined by solving the planning problems included in different sections of the technical, industrial and financial plan. These can be divided into four typical groups.

The first group—*planning the power output*—comprises problems for calculating the expenditure side of the electricity and heat balances and planning

— power consumption by the system, groups of consumers, large consumers;

— heat consumption by the system, separate regions, individual consumers;

— power losses in the system networks, separate areas, tie lines; the system power losses can be planned as a whole including commercial losses;

— heat losses in the system, network areas, accounting for commercial losses;

— auxiliary power of the plant and system;

— required power in view of transfers between systems.

The second group—*planning the performance*—comprises the problems of preparing

— characteristic load schedules for the system, its segments, individual consumers;

— characteristic heat supply schedules for the system, its segments, individual consumers;

— schedules of power transfers within the pool or between system areas with weak electrical couplings.

The third group—*planning the utilization of the energy resources and capacities of the system*—includes

— optimization of water resource utilization (optimization of long-term operation of HPs);

— distribution of electricity load between the stations of the system in view of power flows from other systems (planning of power balances);

— distribution of heat load between TPPs in view of other heating utilities (planning of heat balances);
— preparation of major repair schedules;
— planning of system available capacities;
— planning of system power balances for typical schedules and loads (maximum, minimum, average).

The fourth group—*planning the system fuel resource utilization*—contains
— determination of the fuel balance of the system with respect to equivalent fuel;
— distribution of natural fuel between the system utilities;
— determination of the equivalent fuel consumption for power generation with calculating specific indices;
— determination of the equivalent fuel consumption for heat production with calculating specific indices.

The fifth group—*planning operation costs for electricity and heat production*—comprises
— planning of separate components and total costs for electricity and heat production;
— planning of electricity and heat production costs, net supply incentive funds.

The sixth group—*analyzing technico-economic indices*—is not considered in detail here.

Proceeding from the solution of the above-listed problems the basic technico-economic indices of plants and systems are established:
— electricity and heat production;
— plant availability factor as regards the power and heat loads;
— specific consumption of fuel and water per kWh of electricity and unit heat;
— electricity and heat production costs;
— income of the power system.

The technico-economic indices characterize the effectiveness of control in the power industry. Increased production of electricity and heat indicates a more complete utilization of the fixed assets and in the final analysis raises the national income. Cutting production costs of electricity or heat offers similar results owing to decreased production expenditures.

The availability factor allows for the technical and organizational aspects of production since it accounts for the fullfilment of the maintenance schedules, reduction of power owing to modernizing the equipment, utilization of hidden reserves of power, etc.

Finally the specific consumption of resources is characteristic of the unit and plant efficiencies, feasibility of control, condition of the equipment.

Thus the technico-economic indices may be an important instrument of effective management.

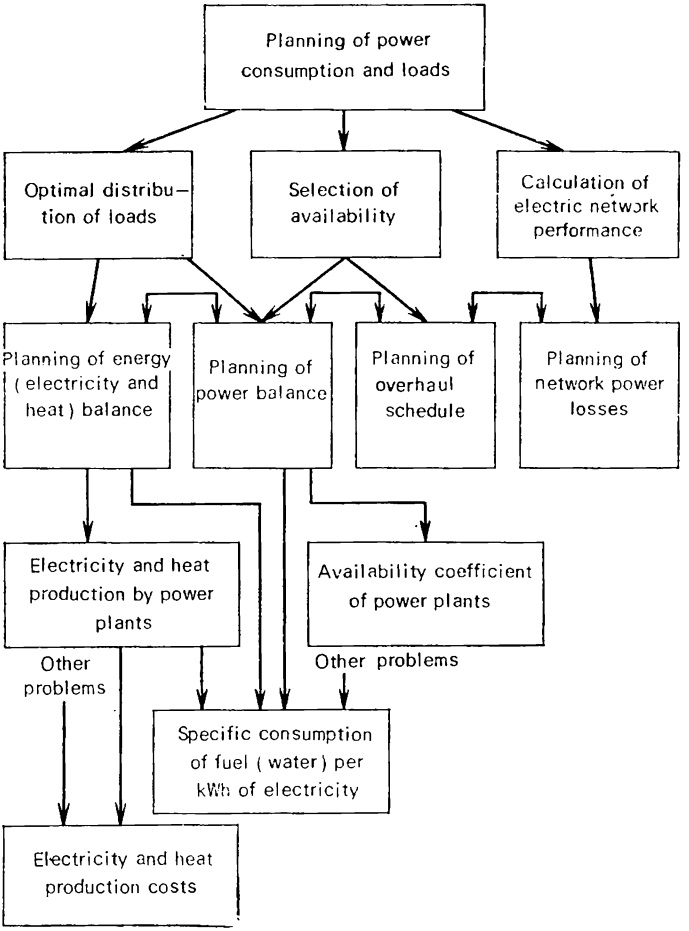

Planning of power consumption and loads
Optimal distribution of loads
Selection of availability
Calculation of electric network performance
Planning of energy (electricity and heat) balance
Planning of power balance
Planning of overhaul schedule
Planning of network power losses
Electricity and heat production by power plants
Availability coefficient of power plants
Other problems
Other problems
Specific consumption of fuel (water) per kWh of electricity
Electricity and heat production costs

Fig. 11.1. Flow chart of planning calculations of performance and technico-economic indices of system

The technico-economic indices are determined by the equipment characteristics, organizational and technical measures, quality of fuel and many other factors. However, the role of operating conditions is also crucial. Therefore, the problems of optimal operation constitute the economic and mathematical basis for the planning calculations.

The optimization problems of planning are solved by the agency of the methods discussed earlier in this book.

Figure 11.1 illustrates a flow chart of planning calculations and the important role of the main operational problems.

The automated system of planning calculations (ASPC) which is being developed at present opens vast possibilities for using the optimization algorithms in solving planning problems and hence will improve the quality of calculations and indices. Besides, with ASPC the planning problems will be handled comprehensively, they will be interrelated by algorithms and information at all the levels of the temporal and spatial hierarchy which will increase the significance of the technico-economic indices in the production management.

11.2. Forecasts in Planning Calculations

The planning process is always forecasting in the essence. On the one hand, the demand for the produce of the branch or enterprise in question, and on the other the production potentialities are to be predicted. The forecast methods are diverse and base on extrapolation, i.e. the ability to look into the future proceeding from the historical and today's information. Many works relating to the energy problems reveal the possibility of wide-scale employment of the probability theory methods and mathematical statistics for solving the planning problems. At present the economico-mathematical models are constructed for forecasting electricity generation and consumption, heat consumption, network losses, auxiliary powers, specific consumption of fuel for power and heat generation, electricity and heat production costs, etc.

Mathematic modeling of the forecast problems allows improving the planning system and opens strong possibilities for computerization of the plant MCS. Draw our attention to some works treating forecast of power demand. These problems are solved using various methods depending on the time period and reliability of forecast. A number of most popular methods in power demand forecasting are briefly outlined below.

Forecast by produce growth factors is made by projecting the growth trend in the past into the future. For instance, if the growth factor K_{T-1} of the power consumption for the past year is known, the forecast for the Tth year

$$C_T = (1 + K_{T-1})\, C_{T-1} . \tag{11.1}$$

and

$$K_{T-1} = \frac{C_{T-1}}{C_{T-2}}$$

where C_{T-1}, C_{T-2} are the consumption for the $(T-1)$th and $(T-2)$th years.

The method is very simple but inaccurate because the data in the past (growth factor K_{T-1}) are applied to the future without any

refinement. On some occasions, this technique offers tolerable accuracy, however, the advent of the computers makes it obsolete.

The power demand is also forecast by the so-called *normative method* which normalizes specific power consumption per unit produce of various enterprises and branches. Now the forecast

$$C_T = \sum_i C_{T,i} F_i \tag{11.2}$$

where i = number of the branch or enterprise
$C_{T,i}$ = forecast specific power consumption
F_i = forecast output

This method is widespread for forecasting power demand for 5-20 years over the entire country and separate areas. It is also applicable to shorter periods but, likewise the first method, involves gross errors. Besides the use of this technique is limited because the power systems are not furnished with information on the expansion of the energy consuming branches of industry.

The mathematical modeling methods find wider use with MCS. These include time series, correlation, statistical modeling and other methods.

The *correlation method* relates the statistical data of power consumption with some main factors affecting the power demand. Extrapolating such relations for the future gives the forecast.

The correlations may exist between the power consumption and gross product, labour productivity, power availability per man, etc. The relation between the power generation and the gross product is more rigid for forecasting 5 to 10 years into the future. For instance, the calculations performed for fifteen republics of the USSR show a correlation factor of 0.9-0.998.

The correlations are also usable for short-term forecasting though the number of the main variables increases with reduction of the forecasting period. Thus, the hydro plant auxiliary power $C_{a.p.}$ depends on the HP operation, availability of house turbines, weather (air temperature, wind speed and direction), etc. However, the ambient temperature t°C is the deciding factor and the correlation $C_{a.p.}$ (t°C) takes the form of the second- or third-order regression.

Forecasting the HP auxiliary power with the predicted temperature yields an error of about 5% if the time period does not exceed one month. This method requires a systematic processing of information to obtain qualitative relations which is offered by MCS.

Forecasting with the use of time series is based on the extrapolation of the latter. The time series is structurally represented as two components taking the form

$$Y(t) = \varphi(t) + V(t) \tag{11.3}$$

Here $\varphi(t)$ describes the determinate component of the series and is called a trend; the component $V(t)$ gives the random deviations from the trend which are probabilistic or indeterminate.

The trend reflects the average steady laws of the value Y variation as a function of time, such as the consumers comprising the system and the basic particulars of their operation, average weather indicators and the like. However, the unsteadiness of many factors affecting the power consumption causes random deviations from the trend, e.g. at the ambient temperature fluctuations.

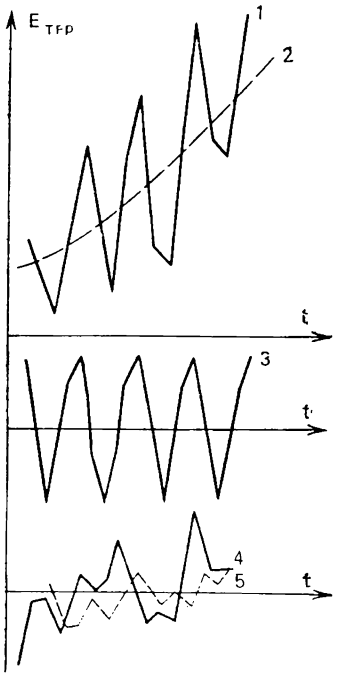


Fig. 11.2. Annual series of monthly thermal power generation in the Novosibirsk Power System

1—initial series; *2*—trend; *3*—seasonal component; *4*—self-regression component; *5*—white noise

If a mathematical model can be selected for $Y(t)$, it is readily applicable for forecasting by extrapolation for a period of $(t + \Delta t)$. The forecast for the moment $(t + \Delta t)$ will be

$$Y_f(t + \Delta t) = \varphi_f(t + \Delta t) + V_f(t + \Delta t) \quad (11.4)$$

where $\varphi_f(t + \Delta t)$ is the value obtained by extrapolating the series $\varphi(t)$ by the moment $(t + \Delta t)$, and $V_f(t + \Delta t)$ by extrapolation of $V(t)$.

We now consider an example time series of thermal plant power generation. The series of annual thermal plant power generation values are given for one of the power systems and cover a period of 10 years. The power generation by the system plants features a persistent growth trend. It is expressed by two components. The first component is linked with the development of the national economy. In the power industry of this country the annual power generation growth on the nation-wide scale reaches 5-7%. The second component averages the climatic conditions of the area (zone) and particulars of consumption. Since the climatic conditions are seasonal, the power generation is heavily dependent upon the seasonal factors during a year. The monthly, weekly and daily power generation is a function of the power consumption.

A random nature of the load and power generation by TPPs is determined primarily by

—the geophysical processes (solar activity, air temperature, river discharge fluctuation, and many many more);

—production activity of the enterprises (changes in labour productivity, interruption in raw material supply, etc.);
—forced outage of the equipment, elements and ties of the system;
—expansion of the power systems and pools.

In view of the above, the time series model takes the form

$$Y(t) = T(t) + S(t) + J(t) + \delta(t) \tag{11.5}$$

All the components of (11.5) are found empirically. The first two components $T(t)$ and $S(t)$ show the steady trends and are called the main trend and the seasonal component, respectively. The random nature of the data are accounted for by the components $J(t)$ and $\delta(t)$. For $J(t)$ the random variable distribution is known and it may be modeled using certain mathematical methods. The component $\delta(t)$ cannot be modeled, since the distribution law is not known. It is the component $\delta(t)$ that determines the forecast error.

The main trend is a polynomial in the time

$$T(t) = a_0 + \sum_{k=1}^{n} a_k t^k \tag{11.6}$$

A polynomial of the order $k = 1$-2 was obtained for the particular example. An example dependence is shown in Fig. 11.2.

The seasonal effect manifests itself on the annual, quarterly and monthly basis. The periodic oscillations are readily visible therefore the second component of (11.5) is a combination of harmonic functions (sine and cosine)

$$S(t) = \sum_{i=1}^{N/2} A_i \cos(\omega_i t) + \sum_{i=1}^{N/2} B_i \sin(\omega_i t) \tag{11.7}$$

where $i = 1, 2, \ldots, N/2$ = number of observation
A_i, B_i = constant coefficients
$\omega_i = 2\pi i/T$, where T is the period of oscillations

The first harmonic recognizes the oscillations with a period of one year, the second with a period of six months (the year is conventionally divided into two periods—winter and summer), the third accounts for quarterly oscillations, etc. The calculations prove that two or three harmonics are quite sufficient for satisfactory accounting of the seasonal effect (Fig. 11.2).

The components $T(t) + S(t)$ give the average power consumption variation and, as mentioned above, reflect regular load changes. The statistical analysis of random fluctuations of the data relative to the average level makes it possible, for the problem treated, to regard the process as stationary. The random stationary process can be regarded, in particular, as an autoregression which allows

revealing the relation of the time series J_t with its preceding levels J_{t-1}, J_{t-2}, . . . and gives the equation of the type

$$J_t = a_{t-1}J_{t-1} + a_{t-2}J_{t-2} + \ldots \tag{11.8}$$

where a_{t-1}, a_{t-2}, . . . are the constant coefficients.

We constructed a model of the third-order autoregression for the example under consideration.

The component $\delta(t)$ is also random but has no mathematical description. It is called white noise.

The following expressions were derived for the TPP generation in one power system

$$T_t = 3622.2 - 50.072t + 2.961t^2$$

$$S_t = 925.409 \cos\left(\frac{\pi}{2}t\right) - 366.801 \sin\left(\frac{\pi}{2}t\right)$$

$$J_t = 0.465J_{t-1} - 0.149J_{t-2} + 0.357J_{t-3}$$

Forecasting the indices by the above relations at the plan drafting stage, i.e. a year in advance, yields an error of not above 5.5%.

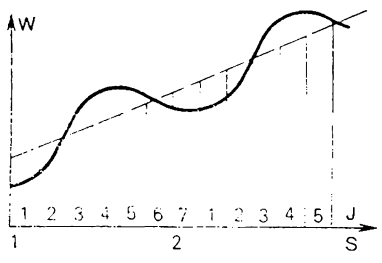


Fig. 11.3. Weekly time series of daily generation

Forecasting daily consumption. The daily consumption curve with a weekly cyclicity is shown in Fig. 11.3. The seasonal oscillations of load are described by a harmonic function of type (11.7) having a period $T = 365$ days, i.e. about 52 weeks. Therefore at short intervals, the sinusoid does not deviate excessively from the straight line and the seasonal variation of load can be represented by a linear function (Fig. 11.3). The weekly oscillations of load are conventionally shown by a sinusoid with a period of seven days. The random component also exists (not shown in Fig. 11.3). The forecast is based on the conversion which gives the relative indices of the power consumption time variation, i.e. the relative value of power consumption on the day in treatment with respect to the consumption during seven preceding days

$$Z(S, J) = W(S+1, J) \Big/ \sum_{J=1}^{7} W(S, J) \tag{11.9}$$

where $W(S+1, J)$ = power consumption on the Jth day of the $(S+1)$th week

$W(S, J)$ = power consumption on the Jth day of the Sth week

All the statistical data are represented in the form of (11.9) and are used to find the respective approximating functions for the seasonal component of the load variation (monthly trend) and weekly (daily) variations.

The seasonal component is approximated by a polynomial of the first or second degree, whereas the daily component by a harmonic function. These functions allow one to estimate the regular load variations over the past period. The random component is described by the autoregression equation.

The base values for forecasting are the data on the consumption during the week preceding the first day of the forecast period

$$V[S, J] = \sum_{J=1}^{7} W[S, J] \tag{11.10}$$

Then the power consumption forecast for the Jth day of the $(S + 1)$th week is

$$W_f[J, S + 1] = [R(J, S + 1) + D(J, S + 1)]\, V[J, S] \tag{11.11}$$

where $V[J, S]$ = power consumption as of (11.10)
$R(J, S + 1)$ = regular component of the load variation
$D(J, S + 1)$ = random component of the load

The similar approach is applicable to forecasting the daily schedules, maximum and minimum loads.

These example mathematical models for forecasting power generation by systems and stations illustrate the philosophy of solving MCS planning problems. Notice that only the formalized models of the planning problems allow computerizing these calculations.

The technical and economic planning can utilize statistical models especially for the indices linked with a plurality of random variables. An example is the system electricity production cost, the curtailed formula of which for a thermal power system takes the form

$$S_t = \sum_i b_{sp,\,i} E_{TPP,\,i} c_i + \sum_j b_{sp,\,j} Q_j c_j + \sum_i I_{c.\,c,\,i} + \sum_j I_{c.\,c,\,j} + \sum_k E_k T_k \tag{11.12}$$

where i = number of TPP generating electricity $E_{TPP,i}$
j = number of the utility producing heat Q_j
c_i, c_j = fuel cost
$b_{sp,i}$, $b_{sp,j}$ = specific fuel consumption per unit electricity and heat
$I_{c.c,i}$, $I_{c.c,j}$ = conventionally constant operation costs
E_k = electricity purchased from other systems
T_k = tariff

Each term of (11.12) includes determinate and random components. The random components dictate the variation and error of forecasts. Their effect upon the general index can be obtained by the statistical modeling method (the Monte-Carlo method).

The problem solution relies on the statistical analysis and includes determining the limit planning errors of each value, finding the function of the forecast error probability distribution, calculating the general index with the use of statistical models.

The planning error is determined by comparing the planned and actual values of the index with reference to the historical data. The maximum errors are assumed to be the limit ones.

A theoretical function of probability distribution for each parameter is chosen inside the limit error area by representative sampling, and its statistic parameters such as the mathematical expectation, variance, asymmetry coefficients, etc., are calculated. Using the mathematical expectations of deviations, we can determine the most probable value of the general index being planned. Then the forecast value of the parameter Z (X) will correspond to the mathematical expectation of the said value Z, i.e.

$$\mathscr{E}(Z) \approx \sum_{r} [X_r + \mathscr{E}(\Delta X_r)]$$

where X_r = forecast of the determinate part of the parameter Z
$\mathscr{E}(\Delta X_r)$ = mathematical expectation of the random component of the value X_r

However, the calculations reveal that such a technique seldom ensures a sufficiently accurate forecast since the values of $\mathscr{E}(\Delta X_r)$ cannot be determined with respect to each parameter individually because the parameters X_r are usually interrelated. Therefore, the statistic modeling algorithms are used for the purpose.

The dimension of the problem can be decreased by utilizing correlations, if any, between the parameters X_r. In such an event, the values correlated to the greatest number of the remaining variables are regarded as independent, whereas the others as the dependent variables. Now only some of the variables have to be modeled for the statistical tests and the others are determined by correlation. The arrays of general values obtained in statistical tests are processed to find their probabilities. The forecast Z will then be

$$\mathscr{E}(Z) \approx \frac{\sum_{m=1}^{d} Z_m(X_r)}{d}$$

where Z_m = general value determined by one realization of the components of X_r
d = number of realizations

Table 11.1

Example Technico-Economic Indices

Parameters	Limit forecast errors, %				Error distribution
	Novosibirskenergo		Kuzbassenergo		
	min	max	min	max	
Power generation	15	—15	2	—16	Uniform
Heat production	—4	—17	2	—16	Uniform
Specific fuel consumption per unit power	—3	—3	0	—4	Uniform
Specific fuel consumption per unit heat	1	—2	0	—1	Normal
TPP generation	—3	—17	2	—16	Gram-Charlier
Power losses	—1	—11	—12	—24	Normal
Heat losses	—5	—19	—2	—10	Normal
Auxiliary power	—5	—22	4	—22	Exponential
Auxiliary heat	0	—16	4	—9	Uniform
Cost of fuel for power generation	1	—6	0	—5	Normal
Cost of fuel for heat production	—2	—5	5	—2	Normal
Operation costs of power generation	—2	—17	12	—6	Gram-Charlier
Operation costs of heat production	15	—38	25	8	Normal

The example of calculating values X_r is given in Table 11.1. These data were used to determine electricity and heat production costs. The forecast error was not above 5%. The statistical modeling of plan indices is possible only with MCS.

11.3. Use of the Power Generation Balance for Planning Technico-Economic Indices

The forecasting methods discussed in the previous section give approximate values of the technico-economic indices. More accurate calculations can be performed using the system power balance data. Notice that prior to handling this problem, we should solve the problems of long-term optimization of HPs, overhaul and medium repair scheduling treated in the previous chapter.

The system power generation balance calculations followed by finding the total and specific fuel consumption can be and are at present performed by two methods.

The first method teaches forecasting the typical electric load schedules to determine thereby the characteristic conditions and different operational data (power generation, efficiency, fuel con-

sumption, water discharge). Average estimates for various indices are obtained on the basis of the characteristic conditions. To this end, the instantaneous characteristics of power plants are used. These are determined by the availability of the equipment and do not recognize the operational corrections (vacuum, outlet air temperature, etc.). Such an approach to long-term power generation and fuel consumption is doubtful because in actual practice not only the load schedules are subject to change. Many other random factors effect the fuel consumption: ambient temperature, cooling water temperature, unit availability, HP operation and many many more. The above-mentioned method essentially neglects them or takes them into account only as regards the load schedule variations. Therefore in many cases the calculation errors are rather high (10% and above).

According to the second method, the sought-for is the power generation over particular intervals, rather than the power schedules. We use here the statistical characteristics of power plants which reflect the operating conditions observed in the past. The historical statistics (average monthly data) is used to construct the energy characteristics of the stations, e.g. fuel consumption versus power generation curves. Since these characteristics are also representative of the power variations, it will suffice to prepare the electricity generation balance for calculating fuel consumption, i.e. there is no need for compiling the power balance of the system. In some instances, such an approach drastically improves the accuracy of solution. Let us consider in brief both of the methods.

A complex system of optimal planning and analysis of main technico-economic indices utilizing daily optimization programs. The system includes several complex programs (Fig. 11.4).

1. *Information programs* make up the source data library. The input information is the normative-and-reference data, actual parameters of all the equipment of the power plants and networks of the system. Programs AT and AK (see p. 278) of the information complex determine the equivalent IRCs of the equivalent fuel consumption, consumption characteristics of units (boilers and turbines) and of the entire plant (AT for heat-electric generating plant, AK for condensation plant). Program Б-3/75 computes partial derivatives of the network active power losses and loads of the transmission lines solving the nodal voltage linear equation set by the Gaussian technique (sequenced elimination of unknowns).

3. *Package of forecast programs* generates the load schedules, and provides short-term and long-term electricity consumption forecasts (hourly, daily, weekly, quarterly, annual and longer). The forecasts are based on the statistical extrapolation, statistical and correlation analysis (risk method, multiple regression, etc.). The programs furnish data for optimal planning of the power system indices and operation control.

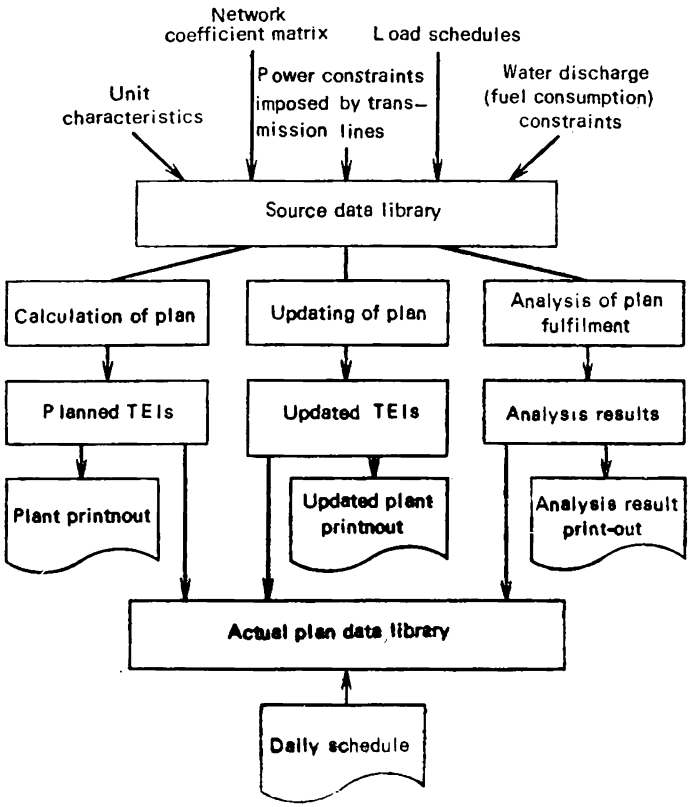


Fig. 11.4. Structure of complex system of planning and analysis of main technico-economic indices
TEI—technico-economic index

3. *Program PLAN-1* computes the annual plan of electricity generation and is intended to prepare proposals for monthly and quarterly generation plans for the power system and its stations. It also determines the power transfers via the main transmission lines, total and specific fuel consumption. PLAN-1 is based on the methods of optimal operation of the power systems. It comprises several independent modules: a library of source data for long-term planning, computation of optimal daily operation of electric station with respect to active power (program B-3/75), computation of planned values, printing out of proposals for the plan.

The backbone of PLAN-1 is program B-3/75. It is intended to calculate optimal daily operation of the power system. The program accounts for the network active power losses, load constraints on the elements of the electric network (transmission lines, transformers), optimizes unit availabilities. The goal of optimizing the power

system operation is to minimize the total expenditures for fuel in view of the main constraints. The optimization is carried out for each hour successively with subsequent verification of the integral constraints. The integral constraints are satisfied by using the Lagrange multipliers and multiple optimization over a given period of time. The gradient method is employed for optimizing one-hour operation. The inequality constraints are accounted for by penalty functions. Program B-3/75 is used both independently and as a standard module of program PLAN-1.

The process of drafting the annual plan of power generation proceeds from day to month, quarter, year. The program successively finds optimal distribution of load between the power plants and corresponding power transfers via transmission line for each characteristic day of the month (working day, Saturday, Sunday, etc.). Then it determines the number of characteristic days in each month and calculates the total power generation and transfer for all the characteristic days. Adding gives the monthly and quarterly power generation and transfer. Concurrently the consumption of equivalent fuel and specific technico-economic indices are determined.

The program accounts for the factors which affect the electric load within a day and during a year (changes in the availability, water regime, weather, variation of incremental rates of the network active power losses, etc.).

4. *Updating of quarterly plans* caused by changes in performance of power utilities. The monthly and quarterly plans of the power system and plants are often subject to updating with respect to electricity generation and intersystem transfers. The plans are updated with the use of system operation optimization methods. The power generation by refined monthly plan for the power system and plants is a sum of power generation over the period preceding the updating and that calculated by the optimization program from the beginning of updating till the end of the planned period. The updated quarterly plan is a sum of the updated plan of the current month and the plans of the remaining months of the quarter. The corrected plan may include only those changes of generation that have been introduced by the orders of the dispatch bodies or dictated by the uncontrolled variables (water regime changes, fluctuations of energy consumption, etc.).

5. *Program ANALIZ-1* checks the fulfillment of the plan and estimates the basics of the economical activity of the power utility (power generation, transfer, total and specific consumption of fuel), detects and analyzes deviation of actual indices caused by uncontrolled variables from the plan. The analysis is carried out by comparing the planned, actual and optimal (for the given conditions) operation of the utility. The calculations comprise two stages. First the effect of the deviation from the optimal conditions on the per-

formance indices is estimated and then are determined the deviations of the actual specific consumption of fuel from the plan dictated by the changes in the operating conditions of the plants and entire system.

All the programs of the system are written in ASSEMBLER and FORTRAN of the EC series computer disk operating systems and are instrumented by the machines of the EC system.

Optimal planning of main technico-economic indices on the basis of statistical characteristics of power plants. *Problem statement.* The system has $i = 1, 2, \ldots, k$ thermal power plants. Known is power generation of the system as a whole for month (or longer) intervals $t = 1, 2, \ldots, n$ of the entire optimization period T. Prepare the system generation balance and determine the equivalent fuel consumption by the plants and the entire system. The plants are given by their statistical energy characteristics.

The mathematical model is as follows.

1. Objective equation

$$B_T = \sum_t \sum_i \overline{B}_{t,\,i} \Rightarrow \min \tag{11.13}$$

Since intervals $t = 1, 2, \ldots, n$ are independent of each other, the optimality criterion may be the minimum of system equivalent fuel consumption for each interval, i.e.

$$B = \sum_i \overline{B}_i \Rightarrow \min \tag{11.14}$$

2. Coupling equations are the energy characteristics of the type $\overline{B}_i(E_i)$, where $\overline{B}$ is the average fuel consumption over power generation interval.

3. Constraint equations:

(a) system energy balance equation for each tth interval

$$E = \sum_i E_i \tag{11.15}$$

(b) energy constraint equation

$$E_{T,i} \leqslant E_i \leqslant E_{a,i} \tag{11.16}$$

where $E_{T,i}$ = forced electricity generation by thermal power plants, e.g. operating in heating cycle

$E_{a,i}$ = generation determined from the plant availability.

4. Optimization equation can be set either by the incremental rate technique or by dynamic programming.

When using the incremental rate method, the optimality condition is

$$\overline{b}_1 = \overline{b}_2 = \ldots = \overline{b}_k = \text{idem} \tag{11.17}$$

where $\overline{b}_i = \dfrac{d\overline{B}}{d\overline{E}}$.

The dynamic programming approach utilizes the main equation to construct the optimal equivalent characteristic

$$B_{eq} = \min \{\overline{B}_i (E_i) + \overline{B}_{i-1} (E_{i-1})\} \tag{11.18}$$

where i is the step of optimization.

The above mathematical model is simple, has a simple algorithm and is easy to computerize. Obtaining the statistical characteristics is the most challenging main part of this algorithm, whereas the optimization per se is relatively simple. Statistical analysis is performed by the system MCS.

Statistical energy characteristics of thermal plants. The effect of the plant operation upon fuel consumption over the interval t manifests itself in the report data. Taking into account a wide diversity of the operating conditions, the statistical information may be thought of as representing changes in the system operation, weather, equipment condition, etc. Therefore, if an object (plant) is not to change its properties in the future, the statistics allows obtaining averaged estimates of some indices of the object. To find the most exhaustive and accurate solution to this problem, we have to choose a feasible form and values of the characteristic and construct mathematical models for them.

In case of TEP, a variety of characteristic parameters is broad. These may include:

(a) a characteristic of equivalent fuel consumption for generating electricity $\overline{B}_i^e$ depending on generation, i.e. $\overline{B}_i^e (E_i)$;

(b) a characteristic of total consumption of equivalent fuel versus electricity generation, i.e. $\overline{B}_i (E_i)$;

(c) a characteristic of total consumption of equivalent fuel versus total energy E_{tot} (thermal energy and electricity), i.e. $\overline{B}_i (E_{tot,i})$; in this case the thermal energy is conversed into electrical one;

(d) a characteristic representing the total fuel consumption less the part spent for supply of reduced-pressure steam; in this case the characteristics will have new varieties, such as $\overline{B}_{RHD,i}$ $(E_{tot,i})$.

Any of the above characteristis can be plotted using the statistics available in the system and plants and utilized for operation planning and analysis.

The choice of the characteristic to a considerable extent determines the success of solution of the entire problem. Table 11.2 exemplifies the use of various characteristics for the Novosibirsk Power Sy-

Table 11.2

Statistical Characteristics Compared

Choice basis	Characteristic type	Season	Mean error of characteristic approximation, %	Mean errors of system fuel consumption planning
Monthly statistics (1970-1975)	$\overline{B}_i^e(E_i)$	Winter	3.91	1.22
		Summer	4.75	—
	$B_i(E_{tot})$	Winter	3.33	1.27
		Summer	3.15	—
Daily statistics (1975)	$B_i^e(E_i)$	Winter	3.52	2.14
		Summer	4.30	—
	$B_i(E_{tot})$	Winter	2.98	4.93
		Summer	3.81	—

stem. The maximum errors for different stations are given, in particular, of all the examples treated characteristics $\overline{B}_i$ ($\overline{E}_{tot,i}$) offer the highest accuracy for planning fuel consumption.

However, constructing the statistical characteristics requires labour-consuming calculations which can be effected only with MCS. These include plotting different curves, selecting the best period in the past for gathering statistics, the best approximating function, and the optimal characteristic for special (test) calculations, updating the characteristics, and some other tasks. All these calculations are fairly bulky. For instance, which parameter averaging period is to be chosen? It may be a day, ten days, or a month. Which information will yield better results? Table 11.2 gives an example characteristic obtained for a rotation month (with a day shift) and for a calendar month (from the first to the last date). We can see that the characteristics differ and to choose the best, we have to perform check calculations for constructing the system generation balance for the typical conditions.

11.4. Automation of Planning Calculations with MCS

Today all efforts are made for creating automated computing complexes to solve the problems of technical and economic planning. The work is still under way so we will consider only one example of such efforts.

The information-computing complex in treatment solves 12 planning problems which give the production cost of system generation. The interrelation and descriptions of the problems are given in

Table 11.3

List of Planning Problems to Fig. 11.5

Problem	Problem description
Б01	Planning power consumption of the system, large loads and ministries
Б02	Planning power consumption by typical daily load schedules of the system
Б03	Planning the system generation
Б04	Planning typical load schedules of the system
Р22	Planning the system power balance by typical days with determining annual consumption of equivalent fuel
Б13	Planning available power of the system
Б30	Planning fuel costs with determining unit prices depending on the types and grades of natural and equivalent fuel
А60	Planning depreciation
Ф50	Planning wages fund
С80	Planning the system production cost
Т40	Calculating average planned tariffs for electricity
Т41	Calculating average planned tariffs for heat
Д70	Planning income and profitableness
Е90	Analyzing profitableness and production cost of the system energy

Fig. 11.5 and in Table 11.3. The algorithms of the main problems are based on the presently adopted planning methods. These are the count-up heuristical procedures with some simple elements of statistical analysis, for instance, planning a certain value with the use of its historical variation coefficient or planning by introducing corrections to the obtained value, etc. These commonly used methods constituted the basis of the algorithms. The only exception is the system energy and power balance problem which was solved by optimization technique (the basics of the algorithm for this problem are treated in Sec. 11.3).

The set of programs was specially provided with individual software using the modular principle on the basis of the single source data bank.

The calculation results are printed out in the form of tables with alphanumeric comments. The automated complex is provided with a set of service routines executing the following functions:

input/output and validity checks;

data exchange between different memories;

control of operation system;

count interrupt with hold.

The solving procedure is automated and the computation run is organized by the dispatcher program which calls to the temporary memory the interpreter and the object programs solving the problems.

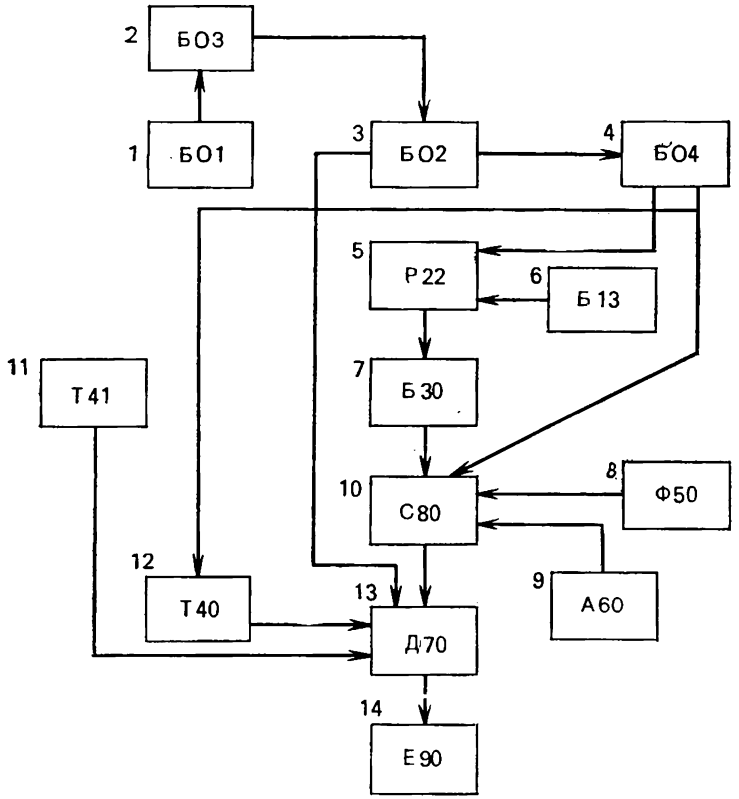


Fig. 11.5. Interrelation of tasks of technical and economic planning in information-computing complex

The main programs of the complex have linkage and replace subroutines which allow setting various modes of the complex operation, e.g. omitting one or several programs and solving one or several problems in the off-line mode.

The count interrupt module is provided with the service routines for holding and recovery of communication information. The complex is divided into four stages by three sets of such routines. The communication information can be held within each stage after execution of any program of the complex. The hold is accompanied by printing of the appropriate commentaries on the accomplishment of the stage and allows one to resume the computations using the communication information recovery routine.

The average run time of the program complex varies with the parameters of the power system (Table 11.4). The calculations performed on a second-generation machine show that the average run

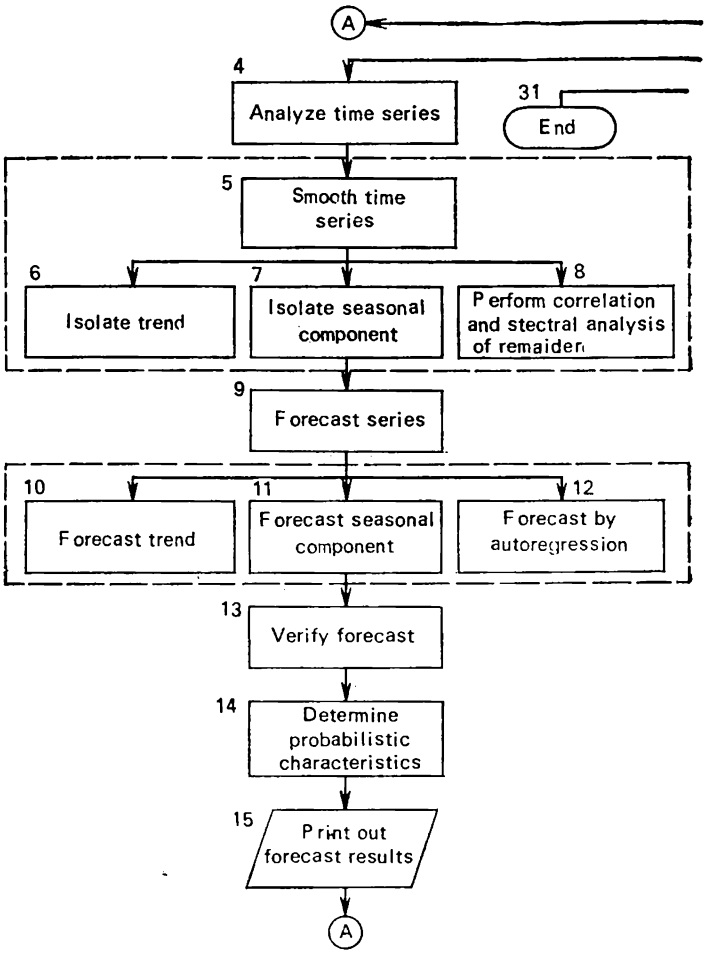


Fig. 11.6. Diagram of ПРОПЭС complex

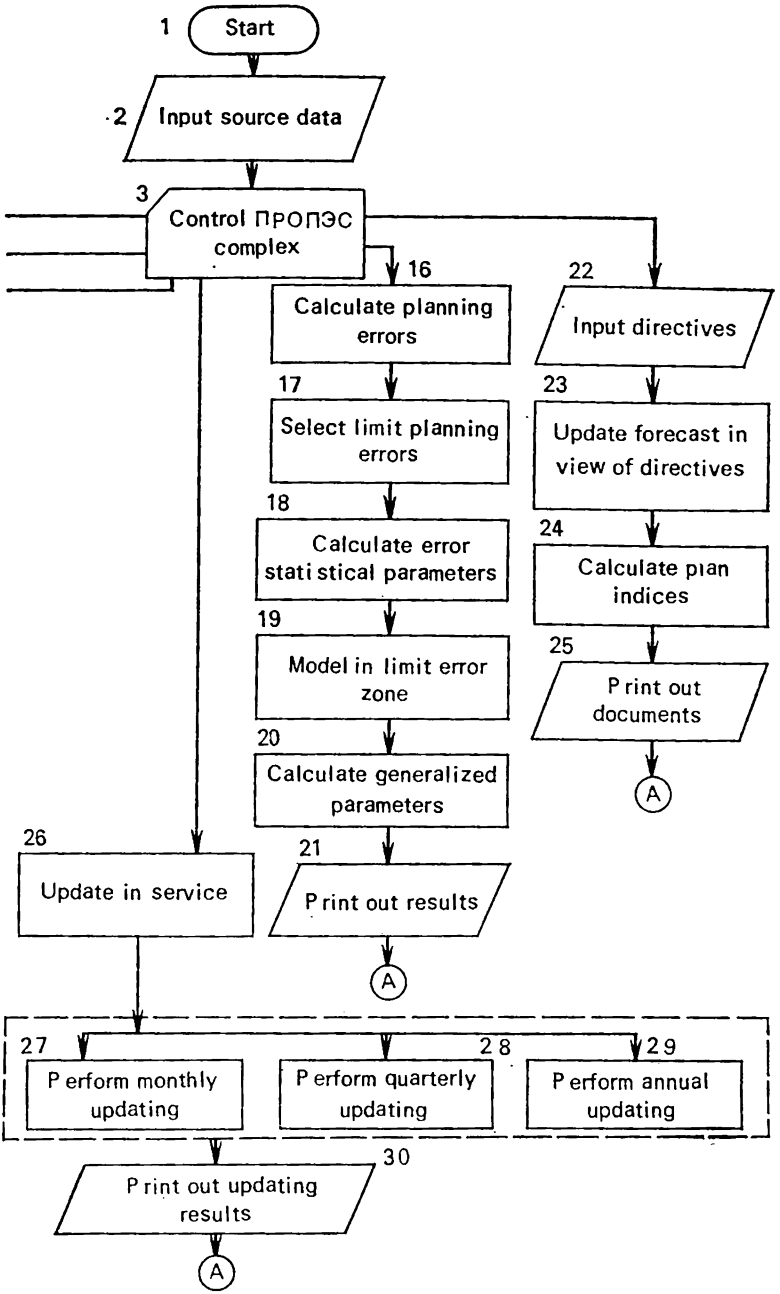

1
Start
2
Input source data
3
Control ПРОПЭС complex
16
Calculate planning errors
17
Select limit planning errors
18
Calculate error statistical parameters
19
Model in limit error zone
20
Calculate generalized parameters
21
Print out results
A
22
Input directives
23
Update forecast in view of directives
24
Calculate plan indices
25
Print out documents
A
26
Update in service
27
Perform monthly updating
28
Perform quarterly updating
29
Perform annual updating
30
Print out updating results
A

Table 11.4

Basic Parameters of Power System Affecting Run Time of Technico-Economic Program Complex

Power system parameters	Irkutskenergo	Krasnoyarsk-energo	Kuzbassenergo
Number of utilities	22	18	16
Number of TPPs	11	5	8
Number of fuel types	6	10	30

time for the Irkutskenergo (power system) is 1 h 54 min, for the Krasnoyarskenergo 1 h 45 min, for the Kuzbassenergo 2 h. The difference in the run time of the fuel cost planning programs is particularly considerable. The calculation and output of the results for 30 grades of fuel in the Kuzbassenergo increase the machine time approximately twofold as compared with the Irkutskenergo where the costs are computed for six types of fuel because of a great number of TPPs included in the system.

The data bank constitutes the backbone of the complex. The heuristical technique requires a large volume of data on coefficients, corrections, increments. This information amounts to 30-40% of the entire bank and is subject to change any time when the planner finds it needs updating. From 7000 to 10 000 machine words are necessary for operation of the complex.

This example reveals that applying manual calculation methods to MCS is often irrational and the designers naturally strive for changing the methodology of the problems to be best suited for MCS. The main trend today is the creation of automated complexes.

An example is the ПРОПЭС* complex.

The presented model comprises a set of programs in FORTRAN computerized on the EC-1020 machine. Structurally the model is a single complex including nine modules which intergrate 28 subroutines. The modules differ in the volume and accommodate the subroutines capable of solving separate problems of the system:

(1) the control module accommodates a control program and a source data input program;

(2) the polynomial regression module serves for calculating a polynomial of successively increasing orders with choosing the optimal degree; the program carries out a regression analysis of a time series, detects the main trend and forecasts it for the required period in advance;

* Russian acronym for Forecasting Indices of Power System.

(3) the module for determining statistical moments, plotting histograms and estimating the normality of the distribution obtained;

(4) the module for calculating and plotting the autocorrelation function includes programs for computing and plotting the autocorrelation factors;

(5) the module of harmonic analysis includes a program for decomposing functions into Fourier series with determining the significance of all the harmonics, ranking by variance growth, selecting the required number of the fundamental harmonics, forecasting seasonal components;

(6) the module of autoregression analysis and forecast of stationary process includes a program for solving the autocorrelation matrix to find the autoregression factors;

(7) the module for smoothing the time series is used for presmoothing values of the process in treatment by various techniques: moving average, exponential smoothing, harmonic weights;

(8) the module for estimating a random component of time series includes checks of the stationarity hypothesis by the ascending and descending series method and of the autoregression factor significance hypothesis;

(9) the plotting module allows one to plot four graphs simultaneously bringing them to a single scale.

The interaction of all the programs in forecasting the power system indices (box *3*) is shown in Fig. 11.6.

The model allows solving four generic problems.

The first problem is forecasting system indices on the basis of time series (boxes *4-15*). Concurrently with the value being forecasted (box *13*) its error is computed (box *14*).

The second problem is providing generic indices of the power system (fuel consumption, generation cost, etc.) taking into account the random nature of the source information (boxes *16-21*). Here are determined the limit errors of separate parameters (box *17*), their random characteristics (box *18*); then the mathematical expectations of the generic indices are calculated using the Monte-Carlo technique (boxes *19-20*).

The third problem is calculating plan indices in view of the directives (boxes *22-25*). Here the results of calculations in boxes *15* and *21* are taken into account and the respective corrections are introduced.

The fourth problem (boxes *26-29*) is updating the plan indices according to the current information.

As transpires from the above, automation of the planning calculations strengthens the role and significance of the operational problems both in obtaining valid source information and optimizing performance characteristics of the system.

12

EFFECTIVENESS OF SOLUTION OF OPERATIONAL PROBLEMS

12.1. Goals of the Effectiveness Calculations

The goals of the effectiveness calculations are varied and include, in particular, the following estimates.

1. **Estimate of optimization algorithm effectiveness.** The algorithm in treatment is compared with a reference one for identical optimization conditions. Since the reference algorithm is seldom available (the mathematical model of the problem is not constructed, there are no suitable optimization methods, etc.), use is made of the algorithm which is the most exhaustive and accurate for a given moment. Reference algorithms can be selected for some few operational problems, for instance in case of the intrastation optimization problem the dynamic programming algorithm can sometimes be referred to. A more common way is to determine a comparative effectiveness of the algorithms suitable for solving the same problems. A number of algorithms and programs have been constructed which allow such a comparison. However, the programs are written in different languages for different machines, have different source data definitions and their comparison is often challenging.

Comparing the results obtained with the use of various programs with the results of the physical experiment looks impracticable for the main operational problems for the lack of accurate data on fuel consumption, water discharge, network power losses, etc.

2. **Estimate of solution errors caused by uncertain and incomplete source data.** Two types of calculations have found wide application: estimating the limit error and calculating the mean estimates. They are solved with the use of the theory of probability, mathematical statistics, game criteria; many analytical expressions have been derived for approximate estimation of errors.

Comparing the solution error with the predicted effect allows one to evaluate the feasibility of particular techniques. The source information on the system load, HP inflow, technico-economic indices, etc. is still far from having adequate accuracy, which necessitates analyzing the effect of the errors upon the optimization results. Some data on the source information errors are given in Table 12.1. The solution errors of different problems (fuel consumption, plant powers, voltages, availabilities, etc.) depend on the type of the

Table 12.1

Source Information Errors

Parameter	Limit errors, %
Specific capacitive conductance of lines	50
Transmission line resistances	20
Plant bus voltage	2.7
Transformer resistances	14
Transformer reactances	9
Plant fuel consumption relative increments	15

objective function and the effect of the errors on the ultimate results and they may prove very considerable as shown in many publications. For instance, the IRC errors cause excessive consumption of fuel from 30 to 90% of the possible economy, the errors of assigning the nodal loads may decrease the optimization results with respect to active power losses by up to 48%. These and other data found in the literature support the need for recognizing the source data error for solving various problems.

3. **Estimate of realization error with the use of particular control means.** One of such problems is comparing the results of solution by the "old" and "new" methods with respect to a selected criterion. These calculations are widely utilized for implementing the programs. The system control means include automatic devices and dispatch control aids. Another problem is comparing the activities of the operating personnel. The operators ensure normal functioning of the system using their knowledge, intuition, instrument readings, instructions, etc. The computer-aided operation usually improves the economic effectiveness of control or makes the system more reliable. Comparing the two results, one can estimate the potentialities of new control methods. However, the effectiveness of utilizing the control strategies recommended by a computer depends on a plurality of objective and subjective factors. The effect of improving the dispatch control is difficult to evaluate to a sufficient accuracy. This can be done only in the form of expert opinion based on the test problem method. However this method involves great methodological and organizational difficulties and does not find wide application.

Another way is to estimate the historical situations, especially the emergency and post-emergency conditions. The effectiveness being sought can be estimated by comparing the actual control strategies with the possible actions within the framework of MCS.

The effectiveness of automatic control depends on the quality of the control programs and the conditions of their implementation.

Abrupt changes in active and reactive powers, energy characteristics of turbines and generators, and other performance characteristics can noticeably change the effectiveness of the control program. When calculating the effectiveness, the planner should take into account the random nature of the source information by applying probability theory and mathematical statistics. These calculations are very important for APCS as they allow one to estimate the expediency of computerizing process control. Besides, they constitute a vital stage in the development and improvement of the automatic control facilities.

The question of realization is crucial because on many occasions very accurate calculations cannot be implemented especially when depending on measuring instruments. The measuring instruments used in the power industry are usually accurate to 2-5%, hence the calculations can be realized only to such an accuracy.

The source data errors may cause considerable discrepancy between the calculated and actual parameters of the system. Table 12.2

Table 12.2

Errors in Measuring Power System Performance Characteristics

Characteristic	Instrument accuracy class	Limit measurement error, %
Nodal voltage, kV	2.5	2.35
Transformer loads:		
resistive, MW	2.5	10.45
reactive, MVAR	2.5	26.60
Station powers:		
active, MW	2.5	6.1
reactive MVAR	2.5	18.0
Branch powers:		
active, MW	2.5	200
reactive, MVAR	2.5	274

Notes: 1. The data were obtained at the Irkutsk power system comprising 47 nodes and 55 branches.
2. The current transformer errors are ± 2% at accuracy class 1.
3. The voltage transformer errors are ± 1% at accuracy class 1.
4. Limit errors include the measuring circuit errors.
5. The instruments for measuring the performance characteristics belong to accuracy class 2.5.

illustrates such a situation. A steady-state operation was calculated for the system and the requisite source data matched the check measurements. The program used the following source information: nodal loads, voltage vector phases at active power balance nodes (balancing nodes), absolute values of voltage vectors at nodes with fixed active power, equivalent circuit parameters. The calculations

gave phases and absolute values of voltage vectors at load nodes and fixed power nodes, active and reactive powers of balancing nodes, branch powers, branch power losses. A comparison of the calculated and measured parameters determined the errors presented in Table 12.2.

We can exemplify a lot of other problems. For instance, MCS should take into account that the algorithmic structure improves and the range of problems widens while gaining experience in operation of MCS, i.e. the calculations should recognize system dynamics.

No procedure of a sufficiently generic application has been yet devised for calculating the economic effectiveness of power installation MCS, therefore only partial economy is determined in most cases.

12.2. Effect of the Energy Characteristics Errors

The procedure for estimating the influence of the source information errors has been elaborated in reasonable detail only for the problem of load distribution between units, stations and systems. Let us consider the impact of the incremental rate characteristic (IRC) errors of a plant upon the optimal distribution of load in a system comprising two thermal power stations I and II (the network power losses are neglected).

If the load is distributed by the actual characteristics the optimality condition is the equality of incremental rates

$$b_r = b_{r,\mathrm{I}} = b_{r,\mathrm{II}}$$

In this case, the load will be distributed as

$$P = P_{r,\mathrm{I}} + P_{r,\mathrm{II}}$$

Assume that the characteristic of the second plant differs from the actual value by the error $+ \Delta b_2$. The load distribution is not optimal (Fig. 12.1), i.e.

$$P = P_{\mathrm{I}} + P_{\mathrm{II}} \text{ at } b = b_{\mathrm{I}} = b_{\mathrm{II}}$$

hence excessive consumption of fuel in the system results. Plant I burns excessive fuel as being additionally loaded with ΔP, while plant II saves it since its load decreases by ΔP. The system on the whole overconsumes fuel

$$\Delta B = \int_{P_{r.\mathrm{I}}}^{P_{\mathrm{I}}} b\,dP - \int_{P_{\mathrm{II}}}^{P_{r,\mathrm{II}}} b\,dP > 0 \qquad (12.1)$$

Transform (12.1) to obtain the analytical expression of excessive consumption versus the characteristic's error. Assume that within the load variation range ΔP (Fig. 12.1) the incremental rate characteristics are linear with the slopes δ_1 and δ_2 for plants I and II, res-

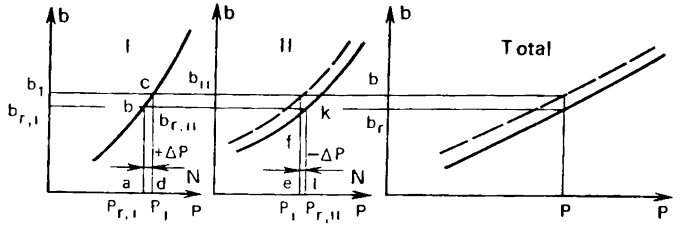


Fig. 12.1. Effect of the energy characteristic error upon load distribution

pectively. The fuel consumption change of the first plant then corresponds to the area *abcd* and is equal to

$$\Delta B_{\mathrm{I}} = b_r \Delta P + \delta_1 \Delta P^2/2 \tag{12.2}$$

The second plant fuel consumption change is represented by the area *efkl* and is equal to

$$\Delta B_{\mathrm{II}} = b_r \Delta P - \delta_2 \Delta P^2/2 \tag{12.3}$$

The value (12.3) is found from the actual (error-recognizing) characteristic of the plant since the fuel consumption changes according to the actual characteristic independently of our knowledge. As transpires from (12.2) and (12.3), excessive fuel consumption in the system

$$\Delta B = \Delta B_{\mathrm{I}} - \Delta B_{\mathrm{II}} = (\delta_1 + \delta_2)\, \Delta P^2/2 \tag{12.4}$$

As seen from (12.4), the characteristic error affects only ΔP and hence can be represented in terms of the error Δb_2.

Figure 12.1 shows that for plant I

$$\Delta P = \Delta b_1/\delta_1 \tag{12.5}$$

whereas for plant II

$$\Delta P = (\Delta b_2 - \Delta b_1)/\delta_2 \tag{12.6}$$

Now from (12.5) and (12.6), we obtain

$$\Delta b_1 = \Delta b_2 \delta_1/(\delta_2 + \delta_1) \tag{12.7}$$

Substituting (12.7) into (12.5), we obtain the relation sought

$$\Delta P = \Delta b_2/(\delta_2 + \delta_1) \tag{12.8}$$

which illustrates that the plant load deviation from the optimum ΔP is linearly dependent upon the incremental rate characteristic's error Δb_2. From (12.4) and (12.8) the excessive fuel consumption in the system

$$\Delta B = \Delta b_2^2/2\ (\delta_1 + \delta_2) \tag{12.9}$$

The excessive fuel consumption for a particular period T

$$\Delta B = \frac{1}{2} \int_0^T \frac{\Delta b_2^2}{\delta_1 + \delta_2} dt \tag{12.10}$$

For several plants participating in load distribution,

$$\Delta B = \frac{1}{2} \int_0^T \frac{\Delta b_i^2}{\delta_i + \delta_s} dt \tag{12.11}$$

where i = plant number

Δb_i = limit error of the incremental rate characteristic of the ith plant

δ_i, δ_s = slopes of the incremental rate characteristics of the ith plant and system with powers obtained at load distribution

Comparing the excessive fuel consumption (12.11) and the possible economy, we can draw a conclusion if the solution is feasible. Expressions (12.10) and (12.11) prove that the excessive consumption depends on the magnitude of the error and increases with the latter. We have already mentioned that the greater is the error Δb_i the more is the difference between the actual powers of the plants and the optimum. The excessive consumption also depends on the slope of the incremental rate characteristics. With steeper curves (greater values of δ), the excessive consumption is smaller that with flatter ones (smaller values of δ). With flatter characteristics the errors cause greater deviations of powers from the optimal value, i.e. give greater values of ΔP.

Formula (12.11) is well adapted to determinate calculations and makes it possible to evaluate the effect of a particular error upon the ultimate results. It is most frequently used for evaluating the influence of the limit errors. Comparing the optimization effectiveness with its limit reduction caused by the source information errors, we arrive at the conclusion that the optimization problem solution is expedient. The limit situations, however, are infrequent in actual practice, which necessitates estimating average effectiveness.

12.3. Limit Error of Power Plant Characteristics

Calculating the errors of energy characteristics for units and plants is a vital stage in solving the operational problems.

Let us consider application of the theory of approximate calculations for estimating the power plant IRC limit errors. Determine the limit error of the plant incremental rates at the system load distribution taking into account the active and reactive power losses. The need for recognizing the network conditions increases the error of the plant differential indices.

Write down the optimality condition at the complex distribution of active and reactive powers of the system taking into account fuel cost variations. This expression is readily obtained using the procedure of Sec. 6.8. Expression (6.97) is a particular case with a fixed fuel cost $c_i = \text{const}$ and only active power losses ($\sigma_{Q,i} = 0$) taken into account.

The optimality condition is

$$b_s = \frac{b_i c_i (1 - \sigma_{Q,i})}{1 - \sigma_i - \sigma_{Q,i}} = \text{idem} \tag{12.12}$$

where i = plant number

b_i = incremental rate of fuel consumption

c_i = fuel cost

$\sigma_{Q,i} = \Delta(\Delta Q_{loss})/\Delta Q$ = incremental rate of reactive power losses ΔQ_{loss} when the reactive power of the ith plant changes by ΔQ

$\sigma_i = \Delta(\Delta P_{loss})/\Delta P$ = incremental rate of the active power losses ΔP_{loss} when the power of the ith plant changes by ΔP

Let each value included in the above expression have an error. The limit value of the relative error of the function $Y(X_k)$ is determined in the theory of approximate calculations from the formula

$$\delta_y = \sum_k \left| \frac{\partial}{\partial X} \ln X_k \right| \Delta X_k \tag{12.13}$$

where X_k is each of the independent values determining $Y(X_k)$.

Taking the logarithm of (12.12) and dropping the subscript i, we obtain

$$\ln b_s = \ln b + \ln c + \ln (1 - \sigma_Q) + \ln (1 - \sigma - \sigma_Q) \tag{12.14}$$

Substituting the partial derivatives with respect to all the variables into (12.13), we get

$$\frac{\Delta b_s}{b_s} = \frac{\Delta b}{b} + \frac{\Delta c}{c} + \frac{\Delta \sigma_Q}{1 - \sigma_Q} + \frac{\Delta \sigma_Q + \Delta \sigma}{1 - \sigma - \sigma_Q} \tag{12.15}$$

wherein the absolute error is

$$\Delta (1 - \sigma_Q) = \Delta\sigma_Q$$
$$\Delta (1 - \sigma_Q - \sigma) = \Delta\sigma_Q + \Delta\sigma$$

Thus, the limit relative error

$$\delta_s = \delta_b + \delta_c + \frac{\delta_Q\sigma_Q}{1-\sigma_Q} + \frac{\delta_{\sigma Q}\sigma_Q - \delta_\sigma\sigma}{1-\sigma-\sigma_Q} \qquad (12.16)$$

where δ is the ratio between the absolute error and the argument value, i.e. the relative error.

From this formula one can easily determine the IRC variation ranges. As also transpires from (12.16), the error of the incremental rates for the system plants can by several times exceed the error of energy characteristic δ_b. In some calculations these "times" reach 3.5.

Consider the *errors of field-test characteristics of the units*. There exist several techniques of field tests of hydraulic turbines, which differ in the methods of measuring the discharge rates. Hydrometric current meter is the most accurate device for such measurements (δ_Q = 1-1.5%). The unit powers can be measured accurate to δ_P = 0.8%. Thus the limit errors of the incremental rates for the units are

$$\delta_q = \delta_Q + \delta_P = 1.8\text{-}2.3\%$$

Widespread today is a method of relative energy tests wherein the discharge rate is determined by measuring a pressure difference in a special measuring section of a volute chamber. In this case the discharge rate

$$Q = kh^m \qquad (12.17)$$

where k and m are the constant coefficients determined by the geometry of the gauge section and embodiment of the unit; h is the pressure difference. The errors

$$\delta_h = 1\%, \quad \delta_m = 0.02\%, \quad \delta_k = 2\%$$

hence the relative error of discharge

$$\delta_Q = \delta_k + m_a\delta_h + \delta_m \approx 2.5\%$$

The incremental rate error rises accordingly to 3.3%.

Since the limit errors are rare, the probabilistic errors that can be implemented with a reasonable validity are of interest. The probabilistic errors can be approximately calculated using the equal-effect method from the formula

$$\delta^* = \delta\sqrt{n} \qquad (12.18)$$

where δ is the limit relative error of the argument determined by the equal-effect principle (it can be found as an arithmetical mean error of the arguments); n is the number of arguments.

In our example, the probabilistic error of incremental rates in field tests is $\delta_q^* = 1.15\sqrt{2} = 1.6\%$, in abbreviated tests $\delta_q^* = 1.65\sqrt{2} = 2.35\%$. These approximate figures prove the existence of the uncertainty zone of the HP unit characteristic.

12.4. Accounting for Random Component in Source Information

Solving the optimization problems in the probabilistic formulation is gaining recognition. System control involves analyzing random variables, functions, processes. In this case, it is impossible to obtain a definite value of the parameters, only their regularities in mass penomena can be estimated. With such an approach it is the optimality criterion expectation that is minimized in solving the optimization problems

$$\mathcal{E}\ (\Phi) \Rightarrow \min \tag{12.19}$$

Satisfying the condition (12.19) indicates that the solution is optimal on the average. Random values of source parameters X^* affect $\mathcal{E}\ (\Phi)$. They obey the known probability laws and may be written as

$$X^* = X_{av} + \Delta X^* \tag{12.20}$$

where X_{av} is the average value of the parameter; ΔX^* random deviations from the average. Expression (12.20) states the problem of estimating the effect of the source information variation (errors) upon the solution.

The method of statistical modeling finds wide application to the problems of recognizing the source information variation. The information errors are often dictated by random factors for which are known the probability distribution laws, their mathematical expectations, variances and other characteristics. At the same time, it is impossible to obtain an analytical expression of the expectation of the value affected by the random realizations of the source data. The remedy is the statistical modeling technique which allows one to find average estimates (mathematical expectations) of particular values. Consider this technique as applied to two problems: load distribution and availability.

Estimating effectiveness of optimal distribution of load accounting for random source energy characteristics of plants. The calculations

are performed as follows. First assume that the unit characteristics are accurate and solve the operation optimization problem proceeding from this assumption. Such a solution is regarded optimal. The next step is to recognize that the characteristics are subject to random changes within the given error range. Using the random characteristics, we can accomplish similar optimization procedure to find excessive fuel consumption with respect to the optimal value. By accomplishing a series of such calculations, we can arrive at the average excessive consumption

$$\Delta \bar{B}_o = B_o - \bar{B} \tag{12.21}$$

where B_o is the optimal fuel consumption; $\bar{B}$ is the average fuel consumption with random characteristics.

The characteristic variations are derived by the agency of a set of random numbers provided by the random-number generator of a computer. The generators of pseudorandom numbers implement the pre-selected probability distribution law and its numerical characteristics. When speaking of random errors of characteristics, it is often assumed that the fuel consumption (water discharge) variation obeys the law of equal probabilities (variations of many performance characteristics may be regarded of equal probability to a first approximation) and the unit power variation obeys the normal law. However, the random values can be comprehended only after analyzing statistics obtained during operation of the stations and the system.

The key aspect of this technique is the probabilistic model of source information, e.g. of the characteristic's variation. If the probabilistic model is not based on the valid data, the statistical modeling will give no solution to the average estimate problem. On the other hand, determining the probabilistic estimates involves labour-consuming analysis of vast amounts of statistics.

In the problem being treated, the characteristic's coordinates (incremental rate and power) are simulated by planar arrangement of two chosen distribution laws within the error ranges of $\pm\Delta b_i$ and $\pm\Delta P_i$ where Δb_i are the errors of incremental rates and ΔP_i are the power errors. The pseudorandom-number generator generates numbers according to the selected distribution law with a zero mathematical expectation and a standard deviation $\sigma = 1$. Performing a great number of tests in which the limit error of characteristics is the same, we can establish the relation between the statistical average of excessive fuel consumption and the error.

Figure 12.2 illustrates the case when a normal probability distribution law is assumed for power P_i and a uniform distribution law for b_i (these two laws are used most frequently). If a normal law is employed, we can state to a probability of $p = 0.9973$ that dev-

iation of the random value from its centre of distribution is, in the absolute value, less than $\Delta = 3\sigma$, where σ is the standard deviation. Knowing the limit error Δ, it is easy to find $\sigma = \Delta/3$. For the uniform distribution law $\Delta = \sigma$.

The random-number generator of a computer generates numbers φ and γ corresponding to a particular probabilistic model which allow one to find the coordinates of a new characteristic. Thus a random value of the incremental rate at $P_i = \text{const}$ is

$$b_i^* = b_i (1 + k_i \varphi_i \Delta b_i) \quad (12.22)$$

and the random value of the power for $b_i = \text{const}$ is

$$P_i^* = P_i (1 + m_i \gamma_i \Delta P_i) \quad (12.23)$$

where b_i and P_i are the given values; Δb_i and ΔP_i are their limit errors; k_i, m_i are the constants depending on the choice of the distribution law.

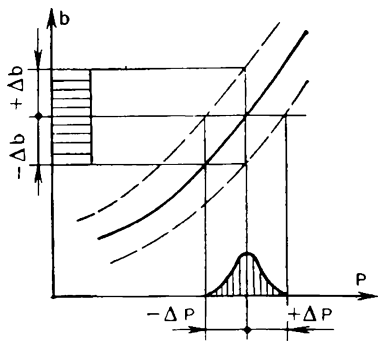


Fig. 12.2. Modeling of the incremental rate random characteristic

The models of the b_i^* (P_i^*) incremental rate characteristics should be checked for monotony. This imposes a constraint on the use of the statistic model. Actually, different points of the characteristic cannot be modeled independently. Various suggestions were made on satisfying the monotony condition. For instance, it is suggested to calculate the characteristic step by step retaining only feasible results, or to model only extreme points of the characteristic while using a satisfactory analytical expressions for its other segments. More widespread is the postulate on equal relative variation of all the points of the curve. In this case a random position is determined only for one point of the characteristic, while the others are changed proportionally to the coefficient $k = X_0/X^*$, where X_0 is the initial number, while X^* is a random number.

If a great number of calculations are performed (some hundred tests are usually required), one can obtain average estimates and their probabilities. For instance, it is possible to find average estimates of excessive consumption of fuel under particular conditions and with particular errors. Figure 12.3 exemplifies such a characteristic which indicates that the increase of the error ΔB raises the average expected excessive consumption $\overline{H}$, %, during distribution of the system load (excessive consumption is given by reference to possible economy ensured by the optimization of ΔB_0).

With a great number of statistical tests, it is convenient to use statistic series in the form of a historgram. The histogram represents

the frequency of a particular value of excessive consumption at a given error (Fig. 12.4). With a great number of tests, the histogram

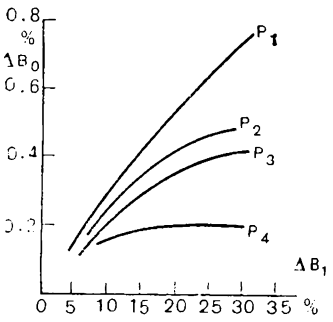


Fig. 12.3. Average excessive consumption of fuel, % ΔB_0, vs consumption characteristic's errors

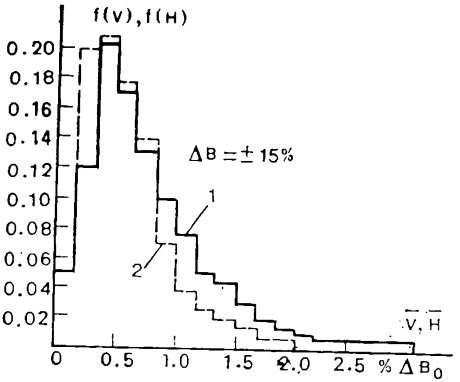


Fig. 12.4. Histogram of excessive fuel consumption vs consumption characteristic's error

1—excessive consumption H when selecting availability; *2*—excessive consumption V when distributing load

takes the form of an excessive consumption distribution density curve and allows one to construct the statistical function of excessive consumption distribution (Fig. 12.5). The latter provides for estimating the probability of excessive consumption for particular conditions.

If the possible effectiveness of optimization δ_B, %, is known, neglecting the power characteristic or using an erroneous characteristic will decrease δ_B by $\overline{H}$. The condition $\delta_B = \overline{H}$ is a boundary condition and the probability $F(\overline{H})$ at this point (Fig. 12.5) is assumed to be the probability of solution effectiveness. Calculations reveal that with 10-15% errors, the deviation from optimal distribution of load in the system is commensurable with the damage inflicted by neglecting the characteristics.

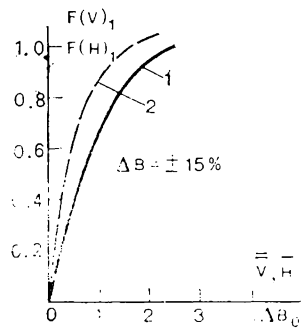


Fig. 12.5. Distribution density of fuel excessive consumption

1—when selecting availability; *2*—when distributing load

Estimating the effectiveness of availability optimization with account of random source energy characteristics. As shown above, such a technique requires bulky calculations, which become more complicated as the number of random parameters increases. An

example is the availability optimization problem. This involves finding the probability of optimal availability for each value of the power and particular error of consumption characteristics. Then excessive consumption caused by non-optimal availability of units is estimated. The above calculation procedure is used for each availability variant. Roughly, one value of power may correspond to some hundred availability variants and each availability variant to some hundred variants of load distribution, i.e. the labour consumption rises more and the calculations become feasible only to support some fundamentals of the calculation methodology.

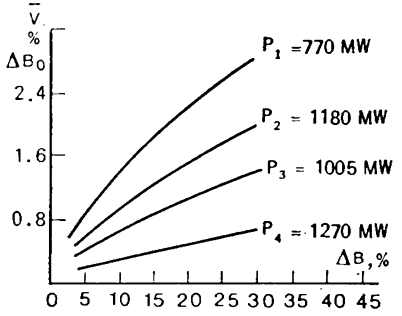


Fig. 12.6. Fuel excessive consumption V vs consumption characteristic's errors ΔB in optimization of availability

Figure 12.6 illustrates the relation between the availability and fuel overconsumption. The availability suited for P_1 and P_2 has to be changed (the number of turbines has to be increased) with P_3 and P_4 because of the load growth. The figure proves that excessive consumption which stems from the characteristics being ignored in the availability optimization problem is far greater than that resulting from neglecting the characteristic in the distribution of load (Fig. 12.2).

In this problem average estimates can also be obtained for the control parameters. For instance, as seen from Fig. 12.7, with HP characteristic errors of $\pm 5\%$ and plant load fluctuations of $+10\%$, the availability error may reach two or three units. A one- or two-unit error is most probable.

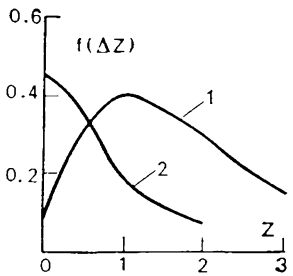


Fig. 12.7. Probability of HP unit number changes with erroneous discharge characteristics of units for
1—Krasnoyarsk Hydro; *2*—Novosibirsk Hydro

The examples presented above demonstrate broad possibilities of using statistical models for estimating effectiveness of the operational problem solutions. However, bulky probabilistic models, high labour consumption and considerable machine time requirements have limited the sphere of the technique primarily to research applications. This method is not used in actual practice. It is therefore obvious that, on the one hand, the information in the energy problems is of a random nature and, on the other hand, bulky calcula-

tions preclude solving the operational problems in the probabilistic formulation. Many investigators today are trying to elaborate methodology for solving such problems in the probabilistic formulation. There are proposals for constructing special characteristics of power installations that would account for a random nature of system loads, or using the statistical linearization method which assumes the probabilistic characteristic to be linear thus drastically decreasing the required number of random realizations, etc. None of these proposals have found wide application in the operational problems up to now and they are not treated in this book.

12.5. Effectiveness Under Uncertainty

On many occasions even a probabilistic description of the source information cannot be obtained, for instance when there is no sufficiently valid statistics or the statistical analysis reveals no probabilistic regularities. Only limit values of the parameters (their variation range) can usually be obtained, therefore this information is called uncertain. Uncertainty problems are usually solved by the minimax criteria. The minimax criteria are widely employed in game theory. They allow one to determine the guaranteed (minimum) effect (win) with uncertain behaviour of the adversary.

Such operational problems have not been yet worked out, therefore we consider only an example solution for estimating various methods of controlling operation and availability of hydro units. Subject to comparison are the use of a generating-unit control computer which automatically selects the required availability and the control under the MSC conditions when the availability can be optimized by the agency of special algorithms and programs for the computer. The second method offers greater possibilities and the task is to estimate its effectiveness.

The comparison requires forecasts of HP loads at least a year in advance, inflow at the dam site, heads, unit characteristics, etc. The long-term forecasts involve gross errors, and the statistical analysis allows one to detect only their ranges. A wide variety and random nature of the factors affecting operation of a hydro plant make the problem uncertain. With two factors uncertain, the problem can be solved successively by using the minimax criteria. The maximum errors in this case reside in loads and heads at a particular inflow at the dam site.

The calculations are carried out in four stages for each calculated hydrograph of HP discharges. At the first stage the probable load schedules and head curves are determined for each selected time interval, at the second, all possible combinations of loads and heads, at the third, electricity economy for each combination with dif-

ferent methods of control, at the fourth, the guaranteed win is determined using the minimax criteria.

Let us discuss the calculation procedure in more detail. Since we deal with random combinations of two states of the performance characteristics, i.e. loads and heads, both being of equal significance and independent of each other, it is possible to use the game theory postulates of two players who obey the severe competition rule. In severe competition games the players cannot gain mutual winning by any coalition. Assume also that the game is noncooperative, i.e. the formation of coalitions between the players is not permissible before the game either. Mark the players by 1 and 2. Meant by 1 is the performance characteristic, i.e. the load schedule, and by 2 is another characteristic, i.e. the head. The set of strategies for them is $A = \{\alpha_1, \ldots, \alpha_n\}$ and $B = \{\beta_1, \ldots, \beta_n\}$, respectively. Each strategy corresponds to one state of the parameter. Mark the end-state (or goal) of the game with a combination of two strategies of different players by $Q_{k,p}$ $\{\alpha_k, \beta_p\}$. The goal of each game is a particular power generation. A matrix may be constructed with its rows and columns giving possible combinations of the parameters:

	α_1		α_m
β_1	$Q_{11}(\alpha_1, \beta_1)$		$Q_{1,m}(\alpha_m, \beta_1)$
...	. . . . .		. . . . .
β_n	$Q_{n,1}(\alpha_1, \beta_n)$	...	$Q_{n,m}(\alpha_m, \beta_n)$

In actual problems separate strategies referred to as pure may have different probabilities. Let $x_1, \ldots, x_m$ be the probabilities of strategies $\alpha_1, \ldots, \alpha_m$ and $y_1, \ldots, y_n$ of strategies $\beta_1, \ldots, \beta_n$. The probability of particular loads in our problems can be determined by the historical data or by statistical modeling. The water head probabilities are determined to a sufficient accuracy from the reservoir drawdawn and filling dispatcher's schedule. Using pure strategies and their probabilities, we can construct mixed strategies $X = (x_1\alpha_1, \ldots, x_m\alpha_m)$ of player 1 and $Y = (y_1\beta_1, \ldots, y_n\beta_n)$ of player 2. Then the average utility of a choice of any mixed strategies is equal to the mathematical expectations for player 1

$$\mathscr{E}_1(X, Y) = \sum_{k,p} x_k a_{k,p} y_p \tag{12.24}$$

for player 2

$$\mathscr{E}_2(X, Y) = \sum_{k,p} x_k b_{k,p} y_p \tag{12.25}$$

where $a_{k,p}$, $b_{k,p}$ is the end-state utility for players 1 and 2, respectively.

Analyzing the mathematical expectations obtained for the mixed strategies of players 1 and 2, determine the guaranteed minimum or maximum gain with varying the strategies of one of the players.

Assume that we aimed at finding the guaranteed effect with respect to a given criterion when the heads are subject to change; now we have to determine the minimum of $\mathscr{E}_2(X, Y)$ which will occur at any variations of the load schedules. To this end, use the minimax criterion

$$V_1 = \min_X \{\max_Y \mathscr{E}_2(X, Y)\} \tag{12.26}$$

Should we aim at calculating the guaranteed effect with respect to a given criterion when the loads are subject to change, the minimax criterion would be

$$V_2 = \min_Y \{\max_X \mathscr{E}_1(X, Y)\} \tag{12.27}$$

Using criteria V_1 and V_2, obtain the guaranteed win.

The minimax criteria are also applicable for estimating the maximum win. It will be

$$V_1^1 = \max_Y \{\min_X \mathscr{E}_2(X, Y)\} \tag{12.28}$$

$$V_2^1 = \max_X \{\min_Y \mathscr{E}_1(X, Y)\} \tag{12.29}$$

The problem considered above was solved for a hydro plant in Siberia (USSR). The effectiveness was estimated by generation. It turned out that generation averaged for a period of many years was 0.2% above (the guaranteed win) that calculated by deterministic methods for a year of average water regime.

12.6. Technical and Economic Effectiveness of MCS

MCS effectiveness indices. The economic effectiveness gained by the development and implementation of MCS is determined by the growth in the social productivity of labour, production, decrease of operation costs, etc.

The economic effectiveness is characterized by three indices:

(1) annual increment (economy)

$$C_{an} = \left(\frac{C_1}{A_1} - \frac{C_2}{A_2}\right) A_2 + P_1 \left(\frac{A_2 - A_1}{A_1}\right) \tag{12.30}$$

where C_1, C_2 = production cost of the annual produce before and after the implementation of MCS
A_1, A_2 = annual product before and after the implementation of MCS
P_1 = profit on the product sale prior to MCS implementation

(2) annual profit

$$Z = C_{an} - E_p K_{MCS} \tag{12.31}$$

where $E_p = 0.12$ is a rated coefficient of yield on capital outlays in the power industry; K_{MCS} are the expenditures for creating and implementing MCS in view of the time factor;

(3) yield of capital investments. The yield condition

$$E_e = \frac{C_{an}}{K_{MCS}} \geqslant E_{MCS} \tag{12.32}$$

where E_e is the estimated effectiveness coefficient; $E_{MCS} = 0.33$ is the rated yield of capital investments for creating and implementing computers and MCS.

The feasibility study involves calculations of particular fixed assets, system operation costs, impact of MCS on production costs, outlays on power industry development.

MCS increases the fixed assets for the price of all the technical facilities required for its functioning, costs of construction or modernization of buildings and structures to accommodate the said facilities, MCS maintenance costs. The total expenditures for MCS include outlays on fixed assets and preproduction expenses for the development, tests and implementation.

When calculating one-time expenditures K_{MCS} for the development and implementation of MCS, their time difference is accounted for by using the coefficient

$$\beta = (1 + E_r)^{T - t_c} \tag{12.33}$$

where E_r is the rated reduction coefficient, t_c is the planned year of commitment of MCS; T is the year of one-time outlays.

Modernizing the control structure and widening the scope of problems handled by MCS yield additional effect of:

(1) cutting operation costs of equipment and structures;

(2) raising the potentialities of the power systems and plants;

(3) increasing generation or improving power conditions of the cheapest plants;

(4) decreasing outlays on power system expansion by optimizing the performance, raising the unit efficiency, etc. For instance, MCS provides for increasing the guaranteed output and displacement power of HPs, decreasing network losses, etc.

The official procedure approved by the Ministry of the Power Industry of the USSR recommends determining the effectiveness by using the *coefficient method.* The effectiveness factors have been found by the expert-opinion method and some of them are included in Table 12.3.

Talle 12.3

Factors for Estimating Effectiveness of MCS in the Power Industry

Factor	Numerical value, relative units
Additional hydro generation owing to optimization of HP and reservoir conditions	0.003-0.01
Reduction of network active power losses	0.03-0.05
Reduction of routine repair costs	0.01-0.02
Reduction of operating personnel costs	0.05-0.01
Reduction of labour costs during overhaul accomplished by self-sufficient method	0.005-0.01
Reduction of expenditures for materials and spares during overhauls	0.02-0.04

All the components of effectiveness are determined from the formula

$$\Delta X_i = X_i \beta_i \tag{12.34}$$

where X_i is the value being considered; β_i is the coefficient of variation of the value X_i due to MCS.

Table 12.3 demonstrates that the effectiveness factors may change by several times and since they are obtained by expert-opinion method, it is not quite clear on what parameter their value depends. This is a grave disadvantage of the coefficient method.

12.7. Scientific and Technological Level of MCS

To estimate functioning of different MCSs and to compare their effectiveness, a special system has been introduced. This system is called a single system of estimating scientific and technological level of management control systems (MCS STL). The estimation is carried out according to a special procedure based on *calculated coefficients* (points) and is very similar to the MCS effectiveness estimation. It should be borne in mind that the adopted method of MCS estimation reflects the present-day level. The development of MCS will alter both the contents and numerical values of the coefficients.

The MCS STL is estimated by a ten-point scale. The estimation refers to the following aspects: a system-technical level, economic potential, level of management automation, organization of production and labour. The MCS STL index is determined from the formula

$$Y_{MCS} = 0.4Y_eY_s + 3Y_m + 3Y_0 \tag{12.35}$$

where Y_e and Y_s are the indices of the economic and system-technical levels; Y_m and Y_0 are the indices of the management automation and organization of production and labour, respectively.

Consider the basics of the methodology for finding the four indices.

The economic level index is determined by relating the rated term of capital outlays on creation of MCS and implementation of computers ($T_{r.MCS} = 3$ years) to calculated T determined from the formula of MCS economic effectiveness

$$Y_e = \left(\frac{T_{r.MCS}}{T}\right)^{1/3} \tag{12.36}$$

The management automation index is found by relating the number of problems that can be computerized for the enterprise of a given class, n_{max}, with the actual number of problems solved automatically, n

$$Y_m = \frac{n}{n_{max}} \leqslant 1$$

It is assumed that for the power system MCSs $n_{max} = 150$. If $n > > n_{max}$, $Y_m = 1$.

The production and labour organization index is assumed to be determined mainly by the power system category. The numerical values of this index depending on the system category are indicated below:

Out-of-category system	0.85
1st category	0.83
2nd category	0.82
3rd category	0.81
4th category	0.80

The system-technical level index is the most difficult to find; it comprises four components which characterize the quality of organizational Y_1, technical Y_2 and mathematical Y_3 supports and the design philosophy of MCS. In view of the weight factors used in the power industry, the index of system-technical level for all the power systems is calculated from the formula

$$Y_s = 0.4Y_1 + 0.2Y_2 + 0.4Y_3 \tag{12.37}$$

The organizational index includes four summands

$$Y_1 = Y_{n.1}\ (P_{1.1}Y_{1.1} + P_{1.2}Y_{1.2} + P_{1.3}Y_{1.3})\ P_{1.4}Y_{1.4} \tag{12.38}$$

or, accounting for the numerical coefficients adopted in the power industry,

$$Y_1 = 0.7\ (0.3Y_{1,1} + 0.4Y_{1,2} + 0.2Y_{1,3} + 0.2Y_{1,4}) \tag{12.39}$$

The value of $Y_{n,1}$ depends on the chosen design philosophy of organizational support and is 1.0 for automated designing, 0.8 for designing based on type plans, 0.7 for prototype-based designing and 0.6 for individual designing. For all power systems $Y_{1,1}$, it is possible to assume $Y_{1,n} = 0.7$.

The coefficient $Y_{1,1}$ determines the organizational level of data preparation: individual—6.0; combined—8.0; centralized—10.0.

For all power systems $Y_{1,1}$ is assumed to be 6 points; one point is added if

—single classifiers are used for solving a set of problems;

—single data set is used for solving the operation planning problems;

—single data set is used for solving information problems on small computers;

—data aggregates are used for management.

The coefficient $Y_{1,2}$ characterizes the utilization of data. It is 5 points for all the power systems. Added to this value are

—from 1 to 3 points when output documents with variable data set are used;

—from 1 to 2 points when CRTs are used for displaying the output information.

The coefficient $Y_{1,3}$ characterizes the fail-over capability of the control system and is estimated as follows:

5.0 if the MCS failure causes system interruptions;

8.0 in case of manual redundancy (change-over to manual control);

10.0 in case of automatic switchable redundancy.

For all the power systems $Y_{1,3} = 8.0$ to which 1 or 2 points are added for redundancy of problems solved on own or rented machines.

The coefficient $Y_{1,4}$ is characterized by a fraction of the optimization problems in the entire set. If the fraction is less than 5%, $Y_{1,4} = 3$, at 5-20%, $Y_{1,4} = 8$, over 20%, $Y_{1,4} = 10$.

The hardware index Y_2 is calculated from the following formula in view of the coefficients used in the power industry:

$$Y_2 = Y_{n,2}\ (0.5Y_{2,1} + 0.3Y_{2,2} + 0.2Y_{2,3}) \tag{12.40}$$

The value of $Y_{n,2}$ is determined likewise $Y_{n,1}$ depending on the degree of automation of MCS hardware designing. The coefficient $Y_{2,1}$ is characterized by the average daily loading of the general-purpose computers and is 2 with the effective time of up to 8 h, 5 for the effective time of from 8 to 14, and 10 for the effective time over 18 h.

If two computers are available, the coefficient is determined by the most loaded machine.

The coefficient $Y_{2,2}$ characterizes the method of connecting the peripheral data collecting facilities with the computing center and is 2 for the non-automatic, 6 for semi-automatic and 10 for fully-automatic communication.

For all power systems $Y_{2,2}$ is 2. Added to this value are:

1 point when using a man-machine dialog system for solving the problems;

2 points when using teleprint data for solving the real-time dispatch problems;

2 points when using teleprint data for solving the production and statistical problems;

1 point in case of a direct input of information to the computer from the teleprinter and DTE;

2 points when using small computers with direct input of telemetry data.

The coefficient $Y_{2,3}$ characterizes the display facilities and its values depend on their type: annunciators—3.0; operation displays—7.0; inquiry-response units—10.0.

For all the power systems $Y_{2,3}$ is assumed to be 7. To this value are added:

1 point for a display system with small computers at the dispatch center;

1 point for a computerized dispatch panel;

1 point for a conversational mode of problem solving.

The software index is calculated from the formula

$$Y_3 = Y_{n,3}\,(0.3Y_{3,1} + 0.5Y_{3,2} + 0.2Y_{3,3}) \qquad (12.41)$$

The coefficient $Y_{n,3}$, likewise $Y_{n,1}$, is found depending on the assumed philosophy of designing the software system.

The coefficient $Y_{3,1}$ characterizes the type of the computer used: for Minsk-32, БЭСМ-4, M-222 machines it is 5; for the unified-system (EC) computers, machines M-7000, M-6000, and second-generation units it is 8.

The coefficient $Y_{3,2}$ characterizes the organization of data processing: local solution—3.0; solution with a single set of norms and standards—5.0; solution with a single information base and data bank—10.0.

For all the power systems $Y_{3,2}$ is 3. Added to these are:

2 points for solving the real-time dispatch problems with a single information base;

2 points for solving the management problems with the information base common for several sets of problems;

1 point for a small computer with a common information base generated by the telemetry data.

The coefficient $Y_{3,3}$ characterizes the programming system: machine commands—2.0; algorithmic languages—5.0; operating systems—10.0.

This coefficient $Y_{3,3} = 5$ for the second-generation computers using algorithmic languages to handle some problems and $Y_{3,3} = 10$ for the second-generation computers and a small computer with an operating system.

13

ENVIRONMENTAL PROTECTION AND OPERATION OF POWER PLANTS

13.1. Power Installations and Environment

When forecasting, planning and controlling operation of the power systems, the planner has to take into account the impact of power installations upon the environment. Therefore, the power industry expansion and operation should be optimized with this in mind, i.e. with due regard for the ecological problems. Among these are the following.

1. The general growth in the energy consumption on our planet is so intensive that in the future the amount of energy generated on the Earth will become commensurable with that received from the Sun. The Sun provides about 0.75×10^{18} kWh per annum. This is about 150 000 as great as the total energy of all kinds of fuel produced and consumed today, so that it is only 0.01% of the energy supplied by the Sun. Though these values are negligible in terms of the Space, the thermal effect of the energy generated on the Earth is considerable especially at separate most energetically stressed areas and results in drastic changes of the microclimate. If energy production is increased by 100-300 times to reach several percent of the solar energy, then, according to calculations of N.N. Semenov, the thermal balance of the Earth will radically change melting polar ice and flooding the entire or a considerable part of the land. This necessitates global optimization of power industry development which should involve not a mere increase in the fuel consumption but the minimization of the latter with as productive utilization of energy as possible. Also, the ecological aspects should be taken into account when arranging power installations over the Earth's territory.

2. The existing energy production processes are not ecologically clean. For instance TPPs pollute air, soil and water. Thus the optimization of the expansion and operation of power industry is aimed at minimizing pollution through the use of electric precipitators, cleaners, etc. and properly locating the power installations so that the effluents do not enter directly into residential districts or large valuable areas of forest. When distributing load between the stations, the planner should not only strive for minimizing the system generation costs but also take into account the impact of each station upon the environment under a particular load. For instance, the

economically feasible shaving of the peak loads by thermal units located near a big city may turn out to be impermissible when they burn fuel containing harmful admixtures, and the air streams may direct the plume to the city. In such a case, the optimal solution is to load a more distant plant which will not pollute the air over the city, despite the adjacent plant generation being considerably cheaper.

3. In addition to the aforementioned chemical and mechanical contamination of the surroundings, thermal plants cause thermal pollution by discharging cooling water at a temperature of 30-40°C to water basins, which is detrimental to flora and fauna.

4. Aerial high-voltage transmission lines and substations are sources of electromagnetic pollution since the high-voltage wires emit electromagnetic waves. These waves exert an adverse effect on living organisms and apparently on plants. They also interfere with the normal operation of radio equipment, such as radio receivers, television sets, communication aids, and various measuring instruments within the radiation effective range.

Thus, the transmission lines need optimization both from the technical, economic and ecological standpoints. The transmission line design should ensure that all the above mentioned effects are inside the permissible limits.

The basic indicator of such permissible limits is the ground-level strength of the magnetic field. The provisional norms effective today specify that the electric field strength (gradient) E should be

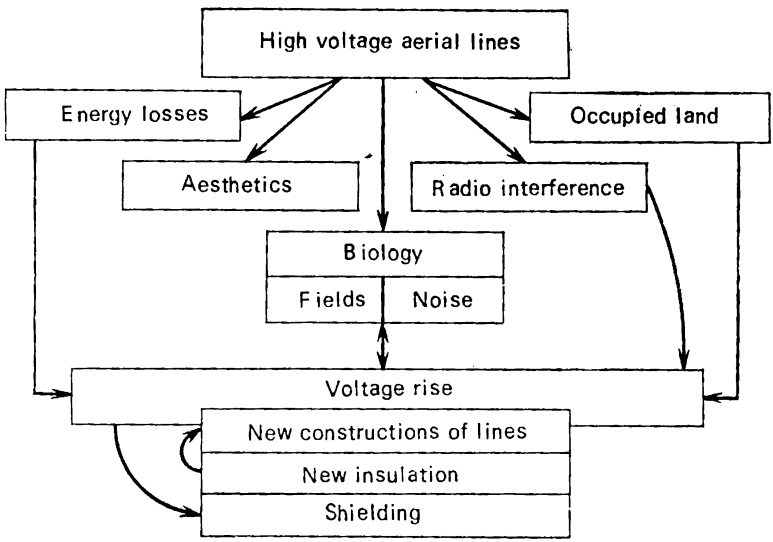


Fig. 13.1 Problems involved in designing modern transmission lines and ways to solve them

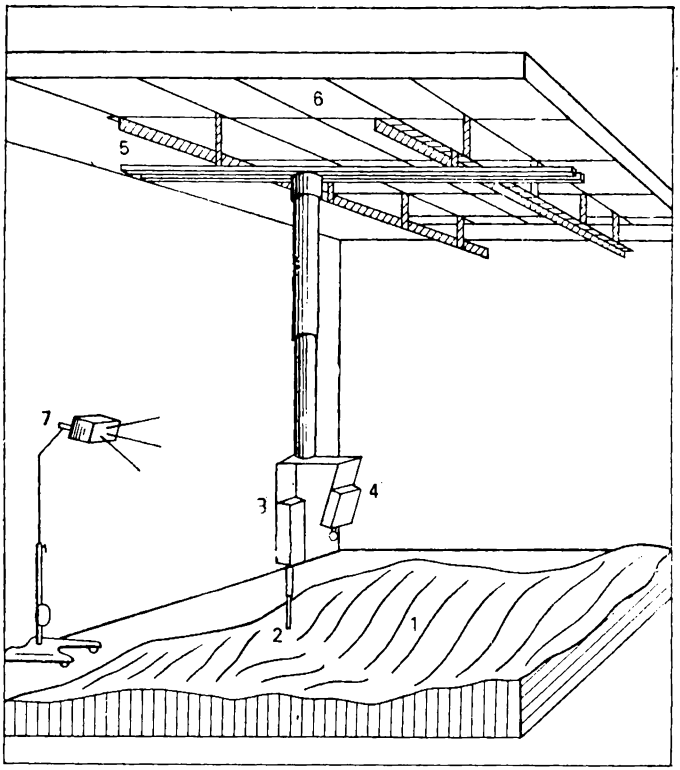


Fig. 13.2. Selection of TL variant in view of landscape

1—mock-up of the construction site landscape; *2*—optical device transmitting the general view of the landscape to the TV camera; *3*—TV camera; *4*—similar optical device transmitting the top view of the structure and landscape; *5*—system for displacing optical devices *2* and *4* of TV camera *3*; *6*—luminous ceiling simulating the sky at various lighting; *7*—special projector simulating the Sun

5 kV/m in the populated areas, 15 kV/m in the areas where the appearance of men is unlikely and can be only seldom and short, and 20-25 kV/m in the areas where prolonged stays of men or domestic animals are virtually excluded (hard-to-reach mountainous regions, water areas, etc.).

Thus, the optimization should be approached on a complex technical, economic and ecological basis. Figure 13.1 shows the problems involved in designing power transmission lines.

Great attention has recently been paid to visual pollution. Any structure, for instance a power transmission line, should aesthetically match the surroundings. It is these considerations that must dictate the configuration and color pattern of supports, their height, arrangement along the line route, while the latter should be so laid out as to meet the local aesthetic requirements to engineering structures. Special models which allow the designer to estimate the structure's

aesthetic impact upon the landscape before erection and compare different variants as regards the surroundings.

Such an installation (Fig. 13.2) provides a clear view of how the particular structure fits the surroundings.

Measures planned for environmental protection. Since 1974 the Ministry of Power Industry and Electrification of the USSR has planned annual measures for protecting the environment. A five-year plan of such measures for 1976-1980 was drawn up in 1975. The environmental protection plan is a component of the technical, industrial and financial plan and comprises the following sections.

1. Protection and rational utilization of water resources—"Water".
2. Protection of the atmosphere—"Air".
3. Protection and rational utilization of lands—"Land".
4. Protection of forests—"Forest".
5. Commitment of environmental protection facilities—"Commitment".
6. Capital outlays on environmental protection—"Outlays".

Let us consider the methodology of developing Sections 1 and 2 which are the most vital for power plants.

13.2. Protection of Water Resources

Water balance. Let us distinguish four typical stages of water utilization: intake, consumption, discharge, waste water treatment.

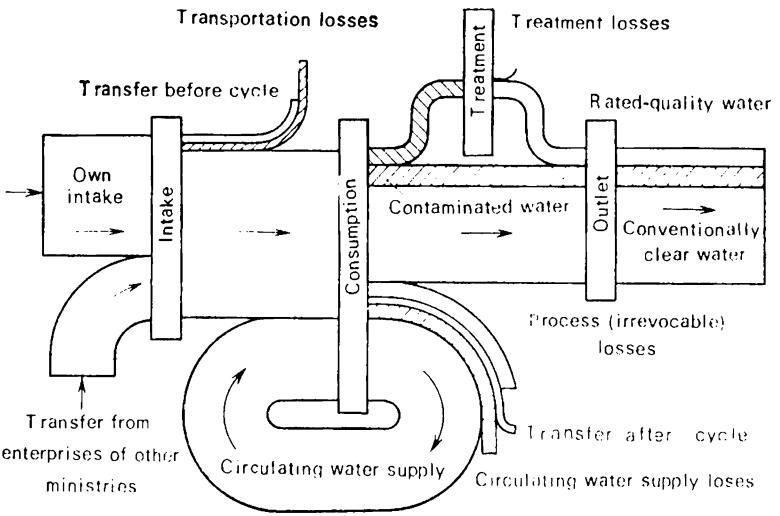


Fig. 13.3. TPP water balance components

Each stage may involve water losses (Fig. 13.3). When preparing the water balance, the planner takes into account the departmental

affiliation of water obtained from the supply points, delivered from other users, waste (treated), and discharge water. In allocation of water there are distinguished conventionally-pure, contaminated and treated (satisfying the approved sanitary norms) water. Circulating water supply comprises a considerable part of the power industry water balance. All the components of the water balance are coupled by balance relations shown in Fig. 13.3.

Water consumption at thermal and nuclear power plants. The water balance at these plants can be written

$$W_{con} = W_{fr} + W_{cir} + W_s + W_{ru} \tag{13.1}$$

where W_{fr} = volume of fresh (added) water
W_{cir} = volume of circulating water
W_{ser} = volume of water used by several series users
W_{ru} = volume of reused water

TPP water supply pattern. The balance structure depends greatly upon the water supply pattern of the plant. There are once-through and circulating water systems. The circulating water system is in turn divided into reservoir (cooling pond) and cooling tower systems.

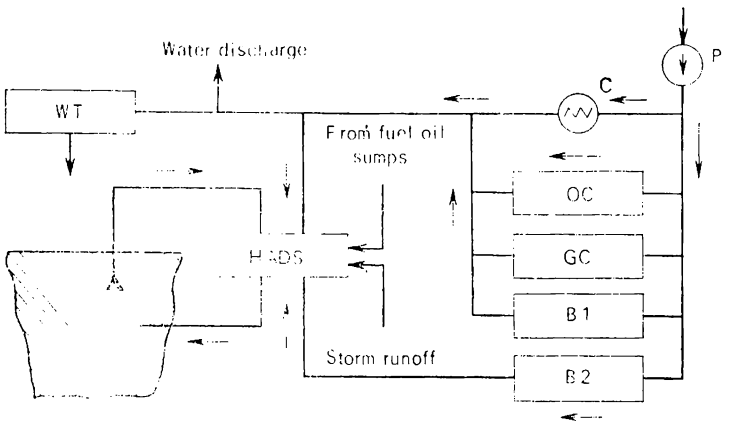


Fig. 13.4. TPP unit water supply diagram

The circulating system with a cooling pond is shown in Fig. 13.4. Pump P supplies water to turbine condenser C, oil coolers OC, gas coolers GC and turbine bearings ($B1$ and $B2$), a part of conventionally-pure water discharged from the condensers, oil- and water coolers is treated (WT) for feeding the boiler and is discharged to the cooling pond. Another part of water will be contaminated with oil or fuel oil and needs to be purified. If necessary the dirty water can be supplied to the hydraulic ash disposal system HADS to make good the loss. This part of water will constitute the series-use water.

Some water is spent for washing the surfaces of the steam generator and its blowing. Wash water is heavily contaminated and can be re-used only after treatment or in the closed system of hydraulic ash disposal without treatment. The system utilizing cooling towers differs in the amount of the series-use water. In such a system, the water passing through the oil- and water-coolers is delivered to the inlet of the pump to be used for cooling the condenser.

TPP water consumers. The main water consumer of a thermal power plant is the turbine condenser. From 100 to 120 kg of water are needed to produce 1 kWh. A thermal power plant with a rated capacity of 2.4 GW requires about 65-70 m^3/s. The other consumers and their requirements, %, are listed below:

Condenser	100
Gas- and water-coolers	2.5-4.5
Oil coolers	1.2-2.5
Bearings	0.3-0.8
Hydraulic ash disposal	0.1-0.4
Steam generators	0.04-0.1
Circulating water supply losses	4-7
Total	108-114

Water consumption rate. To rate water demand, use is made of "Water demand and sewage flow rates" (Table 13.1). Individual norms

Table 13.1

Water Demand and Sewage Flow Rates for 500-, 800-, and 1200-MW Units Operating on Solid Fuel, m^3/MWh for the European Part of the USSR

Water supply system	Circulating water	Fresh water			Irrevocable losses	Water to be treated	
		industrial	drinking	total		industrial	domestic
Once-through	0.31	116.6	0.02	116.62	1.01	0.03	0.02
Circulating with reservoir	115.19	1.72	0.02	1.74	1.14	0.03	0.02
Circulating with cooling tower	114.55	2.15	0.02	2.17	1.48	0.03	0.02
Circulating with air conditioner	70	0.32	0.02	0.34	0.28	0.04	0.02

have been elaborated for some large thermal plants. It is supposed that such rates are to be good for all the stations. If no rates are established, use can be made of the data given in Table 13.2.

The amount of contaminated water. For approximate calculations of water contaminated with fuel oil and oil, we can refer to Table 13.3.

Table 13.2

Approximate Values of Water Consumption for Steam Condensation with Different Types of Turbines, m^3/h

Turbine type	Water consumption	
	hourly, thou. m^3/h	specific, m^3/MW
K-50-90, ПТ-50-90	8	160
ПТ-60-130, T-50-130	8	160
K-100-90, T-100-13	16	160
ПТ-135-130	12.5	93
K-160-130	21	131
K-200-130	25	125
T-250-240	28	112
K-300-240	36	120
K-500-240	52	104
K-300-240	80	100

Table 13.3

Discharge of Water Contaminated with Fuel Oil, m^3/h

Plant capacity, GW	Fuel type	
	Gas/fuel oil	Pulverized coal
1.2	5	3
2.4	10	7
4.0	15	10

Water consumption at hydro plants. To determine HP water consumption, take into account only water used for the process purposes and supplying the HP settlement, neglecting discharge through the plant turbines. Water consumption is made up by process water consumption W_p and drinking water consumption W_d.

Process water consumption. The process water consumers are listed in Table 13.4. About 0.06 l/s of water per 1 kW is needed to cool the generator if HP is situated northward of the 50th parallel and about 0.07 l/s if southward.

From 60 to 65% of the total water demand fall within generator cooling. In view of this, the process water consumption will be

$$W_p = \frac{W_g}{0.6} P_l \qquad (13.2)$$

where W_p = rated water consumption for cooling the generator, l/s
P_l = generator power losses, kW

Table 13.4

Main Consumers of Process Water at HP, %

Consumers	Water-cooled transformers	
	with	without
Generator air coolers	65	77
Unit bearing oil coolers	11	12
Turbine bearing supply	9	11
Transformer oil coolers	15	—
Total	100	100

Calculate losses P_l through the HP installed capacity P_i and hydrogenerator efficiency η_g. The range of η_g is narrow: from 0.95 to 0.98. Assuming a mean efficiency to be 0.965 and taking into account that the losses relate to the generator installed capacity as $P_l = (1 - \eta_g) P_i$, we obtain

$$P_l \approx P_i (1 - 0.965) = 0.035 P_i$$

then

$$W_p = \frac{W_g}{0.6} 0.035 P_i \tag{13.3}$$

or with $W_g = 0.06$ l/s, $W_p = 3.5 P_i \times 10^{-3}$ l/s.

Finally, the annual water consumption, m³/h,

$$W_p = 12.6 P_i T$$

or

$$W_p = 12.6 E_g \tag{13.4}$$

where T = time of the HP installed capacity utilization
E_g = HP generation, MWh

Drinking water consumption at HP. The annual consumption of drinking water is determined from the formula

$$W_y = P_i n_p n_f W_d T_y \tag{13.5}$$

where n_p = personnel coefficient of HP, men/MW
n_f = family coefficient
W_d = daily rate of drinking water, l/day
T_y = number of days in the year

The "Water" section comprises 29 planned indices of which 26 are included in the State Plan and three are for the intrabranch use*.

13.3. Protection of Atmosphere

Pollutants. The TPP plumes can contain various substances. They are partitioned into three main groups.

Particulate matter includes inorganic dust (fly ash). Technological progress leads to reduction of dust particle size which intensifies the detrimental effect of the particulate matter upon the human organism.

Gaseous pollutants include sulfur anhydride (sulfur oxide), nitrogen oxides (the discharge of these gases has recently soared because of the intensified combustion process in the today's steam generators); carbon monoxide (the discharge of the latter is virtually nil for large boilers).

Other pollutants include metals contained in fly ash (vanadium, cadmium, nickel, chromium, arsenic, manganese, barium, cobalt, berillium, etc.) and hydrocarbons.

Maximum permissible concentrations of pollutants. The atmospheric emission should not exceed the maximum permissible concentration (MPC) in the atmosphere. MPCs for some pollutants are given in Table 13.5.

Table 13.5

Maximum Permissible Concentrations of Pollutants, mg/m³

Pollutant	Maximum concentration	Average concentration
Ash, dust	0.5	0.15
Nitrogen dioxide	0.085	0.085
Sulfur dioxide	0.5	0.05
Carbon monoxide	3.0	1.0

In case of a joint emission of nitrogen and sulfur oxides, the following condition should be met

$$\frac{k_S}{MPC_S} + \frac{k_N}{MPC_N} \leqslant 1 \qquad (13.6)$$

where k_S and k_N are concentrations of sulfur and nitrogen oxides respectively, whereas MPC_S and MPC_N are their maximum permis-

* The methodology of planning the environmental protection measures has not yet been finalized, so that the indices are subject to change.

sible concentrations. The formula shows that a joint emission of nitrogen and sulfur oxides decreases the permissible limits for each of them.

General estimate of fuel harmfulness. Particulates and sulfur contents, nitrogen binding capacity and yield of vanadium oxides determine the general harmfulness of fuel. It may be estimated by the following comparative data

Natural gas	1
Kuznetsk coal	2.15
Low-sulfur fuel oil, s up to 0.5%	2.33
Donetsk coal	2.72
Nazarovsk coal	2.89
Fuel oil, s=1%	2.89
Donetsk peat	3.13
Estonian shales	4.75
Fuel oil, s=2.5%	4.86
Moscow basin coal	5.64
High-sulfur fuel oil, s=3.5%	6.17

Note: s stands for sulfur content.

13.4. Atmospheric Emissions

The pollutants rated and checked today include ash, sulfur oxides, nitrogen oxides and vanadium oxides. The gaseous emission is calculated from the characteristics of fuel, furnaces and abatement equipment. The content of carbon monoxide and hydrocarbons is rated only if their emission measuring data are available for the plant. The emission of ash is calculated from the ash collector test data.

Calculation of total amount of ash. The total amount of ash A_t produced at the thermal power plant by the pollution sources depends on the fuel properties and combustion conditions

$$A_t = B\,(A_p + q_4)\,\alpha_c \times 10^{-2} \tag{13.7}$$

where B = fuel consumption for the period planned
A_p = fuel ash content, %
q_4 = fuel losses caused by mechanically incomplete burning, % (usually q_4 = 0.5-5%)
α_c = fraction of ash carried away which depends on the fuel type and furnace design (with dry bottom α_c = 0.95, with liquid bath α_c = 0.7-0.85)

A more accurate value of q_4 and α_c can be obtained from the thermal analysis of the boiler.

Calculation of particulate emission. The following balance of particulates, tons, is written

$$A_e = A_p - A_t \tag{13.8}$$

where A_p, A_t and A_e are, respectively, the amounts of produced, trapped and emitted particulates, t. This is equivalent to

$$A_e/A_p = 1 - A_t/A_p \tag{13.9}$$

The relation

$$A_t/A_p = \eta_c \tag{13.10}$$

where η_c is the average operation efficiency of the ash collector. For cyclones η_c = 60-90%, for scrubbers η_c = 88-92%, for electric precipitators η_c = 96-99.5%, then

$$A_e = A_p - A_p\eta_c = (1 - \eta_c) A_p \tag{13.11}$$

or

$$A_e = B (A_a + q_4) (1 - \eta_c) \alpha_c \times 10^{-2} \tag{13.12}$$

The value of A_t is to be included in the plan. This value is the difference between A_p and A_e or can be determined from the formula

$$A_t = B_f (A_a + q_4) \eta_c\alpha_c \times 10^{-2} \tag{13.13}$$

Calculation of sulfur oxide emission. The sulfur oxide emission is calculated in a similar way. However, it should be borne in mind that 1 kg of sulfur gives 2 kg of sulfur dioxide and a part of sulfur is entrapped with fly ash. In view of this, sulfur emission, t, is

$$A_e = 2BA_S (100 - \alpha_t) \times 10^{-4} \tag{13.14}$$

where A_S is the fuel sulfur content, %; α_t is the coefficient of sulfur entrapped with fly ash, %, which depends on fuel properties and is determined from the following data

Fuel . . .	Shales	Kansko-Achinsk coal	Peat	Other solid fuel	Fuel oil	Gas
α_c	50	20	15	10	2	0

Calculation of nitrogen oxides emission. The amount of nitrogen oxides (as calculated for NO_2) is found from the empirical formula of the All-Union Thermal Engineering Institute (for boilers with a steam-generating capacity $D > 70$ t/h)

$$A_N = 0.143 \times 10^{-6}\beta_1 BQ_h^r (1 - q_4) (1 - \beta_2 r) \beta_3 \frac{12D}{200 + D} \tag{13.15}$$

The dimensionless coefficient β_1 accounts for nitrogen content of fuel, %, and method of slag removal. For gas β_1 = 0.85, for fuel oil 0.8 with the air excess above 5% or β_1 = 0.7 at a lower excess of air; for coals with 1% of nitrogen, β_1 = 0.55 with solid slag removal and β_1 = 0.8 in case of liquid removal. With nitrogen content of 1-1.4%, these values are equal to 0.7 and 1.0, respectively, at nitrogen content of 1.4-1.6% to 1.0 and 1.4, and at [N] 2% to 1.4

and 2.0, respectively. The dimensionless coefficient β_2 accounts for the gas recirculation method. For solid fuel $\beta_2 = 0.010$ if gases are recirculated to the primary air mixture and $\beta_2 = 0.005$-0.008 if gases are fed to the secondary air. The coefficient for gas and fuel oil differs with the method of gas introduction from 0.002 to 0.030. The factor r recognizes the degree of recirculation, %, of blast air flow rate. The coefficient accounting for the burner design $\beta_3 = 1$ for turbulent and 0.85 for straight-flow burners. Q_h^r is the calorific power of fuel, kcal; D is the hourly steam output of the steam generator, t/h.

Rewrite Eq. (13.15)

$$A_N = B(1-q_4)\beta_N \frac{12D}{200+D} \tag{13.16}$$

where $\beta_N = 0.143\beta_1(1 - r\beta_2) Q_h^r \beta_3 \times 10^{-6}$ (13.17)

Emission of vanadium oxides, t, for liquid fuel-burning TPPs is found from the formula

$$A_V = B_f v (1 - \eta_t) \times 10^{-6} \tag{13.18}$$

where v is the content of vanadium oxide in liquid fuel as calculated for V_2O_5; it ranges from 20 to 430 g/t; η_t is the part of particulates trapped by a special precipitator; B_f is the planned consumption of fuel of a given type, tons of natural fuel.

Vanadium oxides are valuable raw material. Therefore the plans should envisage entrapping of vanadium oxides by special precipitators and recycling of wastes. The vanadium oxides heavily contaminate the wash water of the boiler. The trapping and recycling of wash water vanadium oxides should be also included in the plan.

Calculation of carbon monoxide emission. The amount of carbon monoxide A_C is calculated from the following formula derived at the All-Union Thermal Engineering Institute

$$A_C = \gamma c_n B \tag{13.19}$$

where c_n is carbon monoxide emission under normal operation of the boiler, kg/t of natural fuel of kg/thou. m^3 of gas; γ is the coefficient recognizing the combustion conditions and boiler design features. If excess air coefficient α_p is equal to rated one α_r or exceeds it, $\gamma = 0$, if $\alpha_p < \alpha_r$, the coefficient is calculated from the formula

$$\gamma' = \gamma\alpha_p/\alpha_r \tag{13.20}$$

For planning purposes the coefficient c_n can be taken from Table 13.6.

The table is based on the assumption that incomplete combustion of solid fuel in boilers with a capacity of 75 t/h is zero and it does not exceed 0.25% in case of fuel oil or gas. For double furnaces and furnaces with vertical primary furnaces $c_n = 0$.

Table 13.6

Carbon Monoxide Emission c_n, kg/t of Equivalent Fuel or kg/thou. m³ of Gas

Boiler	Coals			Peat	Shale	Fuel oil	Natural gas
	All coal	bituminous	brown				
Grate-fired furnace	22.3	25.7	10.3	16	31	—	—
Chamber furnaces with capacity of:							
up to 75 t/h	0	13.0	5.2	4.1	5.4	19.4	19.9
over 75 t/h	0	0	0	0	0	9.7	8.9-9.3
Hot-water boilers	—			—	—	6-19	5.0-18

13.5. Pollution Control Facilities in the Power Industry

Water pollution control facilities include

1. Effluent treatment plants. There are three types of treatments:
—mechanical purification (sedimentation, filtration);
—mechanico-chemical purification (chemical agents and physical processes, e.g. floatation);
—biological purification (treatment of water with biologically active elements, e.g. activated sludge).

These methods are frequently combined, for instance mechanical purification is complemented with the biological one. This means that when planning the volume of treated water, the planner should refer to the final stage of purification rather than sum up the volumes of separate stages.

2. Circulating water supply systems (cooling, hydraulic ash removal).

3. Treatment plant reclamation units, installations for entrapping and decontaminating plume pollutants, reclaiming valuable components of plume.

Air protection measures. Six typical trends can be distinguished in the air protection field.

1. Improvement of equipment operation. For instance, nitrogen oxide content is directly dependent on the excess air coefficient.

2. Pollution control facilities. This trend involves erecting new facilities and improving the effectiveness of the existing ones. The effectiveness is increased mainly by improving the filters. The filter entrapping coefficient can be increased to 99.5%. However, the outlays on the power station will increase by 7-10% in this case.

3. Increase of the stack height. Increasing the stack height intensifies dispersion of stack gases. There exist stacks over 350 m in

height. However, increasing the stack height from 180 to 250 m increases its cost 3 times, from 180 to 320 m, 6-10 times.

4. Decrease of the fuel sulfur content by its preliminary concentration. For instance, iron pyrite in large fractions can be separated from coal by dressing. Sulfur can be removed from fuel oil by pressure gasification and scrubbing the gas.

5. Removal of sulfur dioxide from stack gases. This process is very complicated and expensive. Up to 140 installations for recovery of sulfur dioxide are known to operate in the world. The gases are treated with activated carbon or bonding of sulfur by magnesite or ammonium reactant. The magnesite bonding technique increases the station cost by 25%. Such installations are metal-intensive. Several experimental installations are under construction in the USSR.

It should be borne in mind that if purification of stack gases from sulfur and construction of a high stack are approximately equal with respect to the maximum permissible concentration and costs, the first way is preferable because a high stack will only disperse the plume rather than diminishing pollution.

6. Creation of sanitary (pollution prevention) zones.

13.6. Environmental Protection and Operation of Power Plants

When planning operation of power systems and plants, their impact upon the surroundings should be taken into account. Optimal operation of thermal plants can be directly affected by the air pollution abatement measures. Operation of hydro plants depends on fish protection measures.

The harmful ecological effect caused by emission of particulate and gaseous pollutants can be diminished by adequate distribution of load between the plants of a power system. However, this will lead to a noticeable excessive consumption of fuel because taking into account pollution factors will change optimal distribution of load.

To take into account the ecology considerations, let us estimate total expenditures involved in burning of fuel. These expenditures comprise fuel costs and expenses (damages) caused by pollution. When combusting solid fuel of cost c these expenditures will be

$$T_f = B\,(c + A_a a_a \alpha_a + A_S a_S \alpha_S + A_N a_N \alpha_N + A_C a_C \alpha_C) \tag{13.21}$$

where A_a, A_S, A_N, A_C are particulates, sulfur, nitrogen and carbon emitted to the atmosphere, kg/t of equivalent fuel, which are calculated from the above formulae; B is fuel consumption; a_a, a_S,

a_N, a_C are mean values of damage caused by emission of particulates, sulfur, nitrogen and carbon, respectively; α_a, α_S, α_N, α_C are coefficients of average damage of the same pollutants depending on the local conditions (general background of air pollution, population density, industry density, stack heights, prevailing wind characteristics, etc.). The same coefficients are used for taking into account the preset state of the atmosphere in short-term planning. Then

$$T_f = BcK_c \tag{13.22}$$

where K_c is the coefficient for fuel cost in view of pollution. For solid fuel the coefficient

$$K_c = 1 + A_a a_{0.a}\alpha_a + A_N a_{0,N}\alpha_N \quad A_C a_{0,C}\alpha_C + A_S a_{0,S}\alpha_S \tag{13.23}$$

In this expression zero indicates the mean value of damage in fractions of fuel cost. On most occasions, with large boilers the second to last term accounting for carbon oxide emission can be neglected. Coefficient K_c can be written as follows (see Sec. 13.4):

$$K_c = 1 + (A_a + q_4)(1 - \eta_f)\alpha_{ca}a_{0,a}\alpha_a \times 10^{-2} \quad (1 - q_4)\beta_N \times \frac{12D}{200 + D} a_{0,N}\alpha_N + \gamma C_n a_{0,C}\alpha_C + 2A_S(100 - \alpha_f) \times 10^{-4}a_{0,S}\alpha_S \tag{13.24}$$

where A_a and A_S are the estimated ash and sulfur content of fuel, %; q_4 is the coefficient of combustible loss, %; α_{ca} is fraction of carried away ash; η_f average efficiency of the filter; D is the steam-generating capacity of the boiler, t/h.

In case of liquid fuel where particulates are nil but vanadium oxides emission is great, the formula will be:

$$K_{c,l} = 1 + A_N a_{0,N}\alpha_N \quad A_S a_{0,S}\alpha_S \quad A_V a_{0,V}\alpha_V + A_C a_{0,C}\alpha_C \tag{13.25}$$

For liquid fuel the coefficient will be

$$K_{c,l} = 1 + (1 - q_4)\beta_N \frac{12D}{200 + D} a_{0,N}\alpha_N + 2A_S(100 - \alpha_f) \times 10^{-4}a_{0,S}\alpha_S + v(1 - \eta_f) \times 10^{-6}a_{0,V}\alpha_V + \gamma C_N a_{0,C}\alpha_C \times 10^{-3} \tag{13.26}$$

where v is the specific consumption of vanadium oxides in fuel; η_f is the coefficient of entrapping of vanadium by special filters.

On most occasions the coefficients which dictate local factors for different pollutants can be assumed equal, i.e. $\alpha_a \approx \alpha_S \approx \alpha_N \approx \approx \alpha_C \approx \alpha$.

Then finally for solid fuel

$$K_{c,s} = 1 + (A_a a_{0.a} + A_S a_{0,S} + A_N a_{0,N} + A_C a_{0,C})\alpha \tag{13.27}$$

for liquid fuel

$$K_{c.l} = 1 + (A_N a_{0,N} + A_V a_{0.V} + A_C a_{0.C})\alpha \qquad (13.28)$$

The condition of optimal distribution of load between power plants in view of environmental protection will be

$$\sum_{i=1}^{n} B_i K_{c,i} \Rightarrow \min \qquad (13.29)$$

The control equation for the convex problem will be

$$K_{c,i} b_i = \text{idem}$$

i.e. will be apparently similar to the law of the best load distribution between plants with different cost of fuel. With such an approach, coefficient K_c is calculated, fuel cost is corrected and the load distribution is performed by reference to this corrected cost in a conventional manner. The method is very simple but has two shortcomings:

1. It is assumed that the thermal unit loading does not affect the pollutant emission. This assumption is not stringent enough because thermal parameters of the boiler change with load. It is also assumed that the precipitator efficiency remains constant at all loads.

2. Pollution fighting is confined to redistribution of load between power plants. However emission of nitrogen oxides is considerably dependent on the excess air coefficient. Principally, the effect of the excess air coefficient upon the emission of nitrogen oxide can be taken into account. However, it should be borne in mind that changing the excess air coefficient changes the thermal unit efficiency and fuel consumption, i.e. variations of the unit consumption characteristics should be accounted for.

From the above it transpires that the methodology of recognizing ecological problems at load distribution in power systems is still in its infancy and needs scrupulous study. For training purposes, we can assume that $a_a \approx a_S \approx a_N \approx a_C \approx a_V = a$.

Note that accounting for pollution at the distribution of load is a particular case of the vector optimization. Here we used the method of weighting local objective functionals by the product of weight factors.

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